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NIST U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards and Technology

Office of Applied Economics
Building and Fire Research Laboratory
Gaithersburg, Maryland 20899

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Abstract

Many new materials are being developed from polymers, metals, and ceramics. Industry is beginning to introduce some of these high-performance or new-technology materials in construction and manufacturing applications because the materials have advantages over traditional materials like steel, concrete, wood, and aluminum.

However, many high-performance materials have not been used in large-scale construction projects. Economic and technical barriers hinder industry's aggressive introduction of these new technologies despite their advantages over traditional materials. The primary economic barrier preventing the use of new-technology materials is their high initial cost. Regardless of how cost effective a material might be over the life cycle of the project, industry balks at high up-front costs, particularly when the life-cycle costs of a new material are relatively uncertain. This cost barrier inhibits construction applications of—and eventually research in—new materials. Yet the construction industry has many potential applications: for example, fiber-reinforced polymers (FRPs) and high-performance concrete and steel are technically viable substitutes for conventional bridge materials. FRPs are also likely candidates for use in marine structures and offshore oil rigs. Germany and Japan are leading the world in FRP use in construction; if U.S. companies are to remain globally competitive, they too will likely need to introduce new-technology materials in their construction projects.

To overcome this cost-based barrier to the adoption of new materials, the construction industry needs practical economic methods for evaluating alternative building and construction materials in a comprehensive and consistent manner. Providing a guideline for determining life-cycle cost effectiveness will give decision makers a tool to help them select, both for research and construction applications, those materials that will make firms competitive and help government agencies deliver the nation's infrastructure at minimum life-cycle cost. This report provides such a method for evaluating the life-cycle cost effectiveness of new-technology materials in relation to conventional materials. The method provides users with a tool that helps them choose that material among competing alternative materials that performs the required function at minimum life-cycle cost.

This method can be used to satisfy the Intermodal Surface Transport Efficiency Act's requirement that life-cycle costs be considered in the design of transportation-related structures, and Executive Order 12893 which requires that the costs of federal infrastructure investment be accounted for over the life span of each project. The method is consistent with ASTM Standards for computing life-cycle costs.

A three-level, hierarchical cost classification presents the types of costs that characterize the use of conventional and new-technology materials; this helps analysts identify all of the costs—including spillover costs to project users and others—that are appropriate for an economic analysis. An economic case study of bridge decks evaluates the use of three FRP materials as alternatives to conventional concrete. A sensitivity analysis shows how significant various cost items are toward making FRP composite decks economically competitive. Suggestions for further research in the economics of new-technology materials completes the report. The methods presented are equally applicable to non-construction materials and projects, as well as the evaluation of any capital budget expenditure as long as the performance of each competing alternative meets project requirements.

Preface

This report, prepared under the sponsorship of the High-Performance Construction Materials and Systems (HPCMS) initiative at the National Institute of Standards and Technology (NIST), provides a general method for evaluating the life-cycle cost effectiveness of new-technology materials in construction. The method provides users with a tool that helps them choose that material among competing alternative materials that performs the required function at minimum life-cycle cost. A case study that compares the life-cycle costs of FRP and conventional material bridge decks illustrates the economic method. A hierarchical cost classification presents the types of costs that characterize the application of conventional and new-technology materials in building and construction. It helps analysts identify all relevant costs for an economic analysis.

Although the focus of this report is on construction applications of new materials, the methods presented here are equally applicable to non-construction materials and projects. These same principles apply in the evaluation of any capital budget expenditure as long as the performance of each competing alternative meets project requirements.

The report is an interdisciplinary approach to decision making in construction and building. The authors (see professional profiles of the authors in Appendix A) blend economics and engineering in the development of a methodology designed for use by construction project planners, designers, and specifiers of materials. A glossary of technical terms (Appendix B) helps bridge the gap in communication between disciplines.

Acknowledgments

Thanks are due to Shyam Sunder, Joannie Chin, Jon Martin, Geoffrey Frohnsdorff, and other members of the NIST materials research team in the Building and Fire Research Laboratory who taught us about FRPs and introduced us to the types of cost savings that new-technology materials might bring to construction.

Special appreciation is due to the following members of the composites industry—Doug Barno of the Composites Institute; Frank Belknap and Dr. Vistasp Karbhari of the University of California at San Diego; Karl Bernatich of Hard Core Dupont Composites, Inc.; Rick Johansen of E.T. Techtonics; Dr. Iyer of the South Dakota School of Mines and Technology; Dr. Nabil Grace of Lawrence Tech University; Gerald R. Miller of Bedford Reinforced Plastics, Inc.; Dr. A.A. Mufti of the ACMBS Network of Canada; Guiseppe Palmese of the University of Delaware's Center for Composite Materials; Dale Ryan of Polymer Bridge Systems; Joe Showers of J. Muller International; Michael Sprinkel of the Virginia Transportation Research Council; and Brian Wilson of Wilson Composites Group, Inc.—for their tutoring in the mechanics of composites and their application to bridge decks. Additionally, thanks are due to Debbie Barbour, Don Idol, and Charles Hunt of the North Carolina Department of Transportation; Dr. Lawrence Bell of Clemson University; Steve Chase of Turner Fairbanks Highway Research Center; Dr. Hota Gangarao of West Virginia University; Jose Gomez of the Virginia Department of Transportation; Loren Hill of the Minnesota Department of Transportation; Scott Milkovich of the BIRL Industrial Research Laboratory; Eric Munley and George Romack of the Federal Highway Administration; Frank McHale of Hawaiian Dredging and Construction Company; and Mike Lee and Frank Limacher of the California Department of Transportation for their assistance in applying composites to infrastructure projects, and in computing the life-cycle costs of bridge decks.

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1. Introduction

1.1 Background

New-technology materials are being developed from polymers, metals, ceramics, and composites of these materials. Industry is beginning to introduce some of these high-performance or new-technology materials in construction and manufacturing applications because they have attributes such as high strength and stiffness, light weight, long service life, and low assembly and maintenance costs. These characteristics can give new-technology materials significant advantages over conventional steel, concrete, wood, and aluminum.

Yet most new-technology materials have not been applied in large-scale construction projects. Economic and technical barriers hinder industry's aggressive introduction of these new technologies despite their advantages over traditional materials. New-technology materials typically have high initial costs. This is a major barrier: regardless of how cost effective applications might be over the life cycle of the product, industry balks at high up-front costs, particularly when the life-cycle cost of a new material is relatively uncertain. This cost barrier deters applications of, as well as research in, new materials. Another barrier is that engineering designs using new materials are often new and require more design time. Finally, industry incurs a risk of failure when using new-technology materials that have not been tested over time.[1]

Despite these barriers to using new-technology materials, the construction industry has many potential applications. Fiber-reinforced polymers (FRPs) and high-performance concrete and steel, for example, are technically viable substitutes for conventional materials in bridges. FRPs are also likely candidates for use in marine structures and offshore oil rigs. The increasing importance of Life-Cycle Assessment, which requires consideration of the environmental effects of materials from production to disposal or recycling, also encourages the consideration of new-technology materials. Countries such as Japan and Germany are aggressively introducing advanced materials in construction applications. If U.S. companies are to remain globally competitive, they too will likely need to introduce advanced materials in their construction projects.

These new-technology materials could play a significant role in replacing the aging transportation infrastructure in the United States. Federal mandates, including the Intermodal Surface Transport Efficiency Act of 1991 (ISTEA)[2] and Executive Order 12893, "Principles of Federal Infrastructure Investment,"[3] require consideration of all costs over the life span of a federal project, including replacement of roadways and bridges. If new materials such as FRPs or high-performance concrete are shown to be cost effective vis-a-vis conventional methods, their use could significantly reduce the cost of maintaining this infrastructure.

Figure 1 illustrates how the consideration of new-technology materials is an integral part of the construction process. Customer Needs, represented in the upper left-hand box, lead to a formal Design Process in which a facility is planned and proposed to satisfy those needs. During the Concept Planning stage, the basic form and function of the facility is outlined. During the Preliminary Design phase, alternative construction

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[1] Even though fiber-reinforced polymers (FRPs) have been tested and used in the aerospace industry for the past 30 years, predicting the material's behavior in infrastructure applications requires additional testing.
[2] Intermodal Surface Transportation Efficiency Act of 1991, Pub. L. No. 102-240, 150 Statute 1914 (1991).
[3] Executive Order No. 12893, Federal Register 59,020 (1994).

materials (e.g., concrete, steel, wood), and different configurations of those materials are considered. Finally, actual structural member sizes, connection details, and assembly instructions are outlined during the Parametric Design phase. The structure or facility resulting from this design process passes through several distinct phases in its Project Life Cycle: Construction; Operation, Maintenance, and Repair; and Disposal.

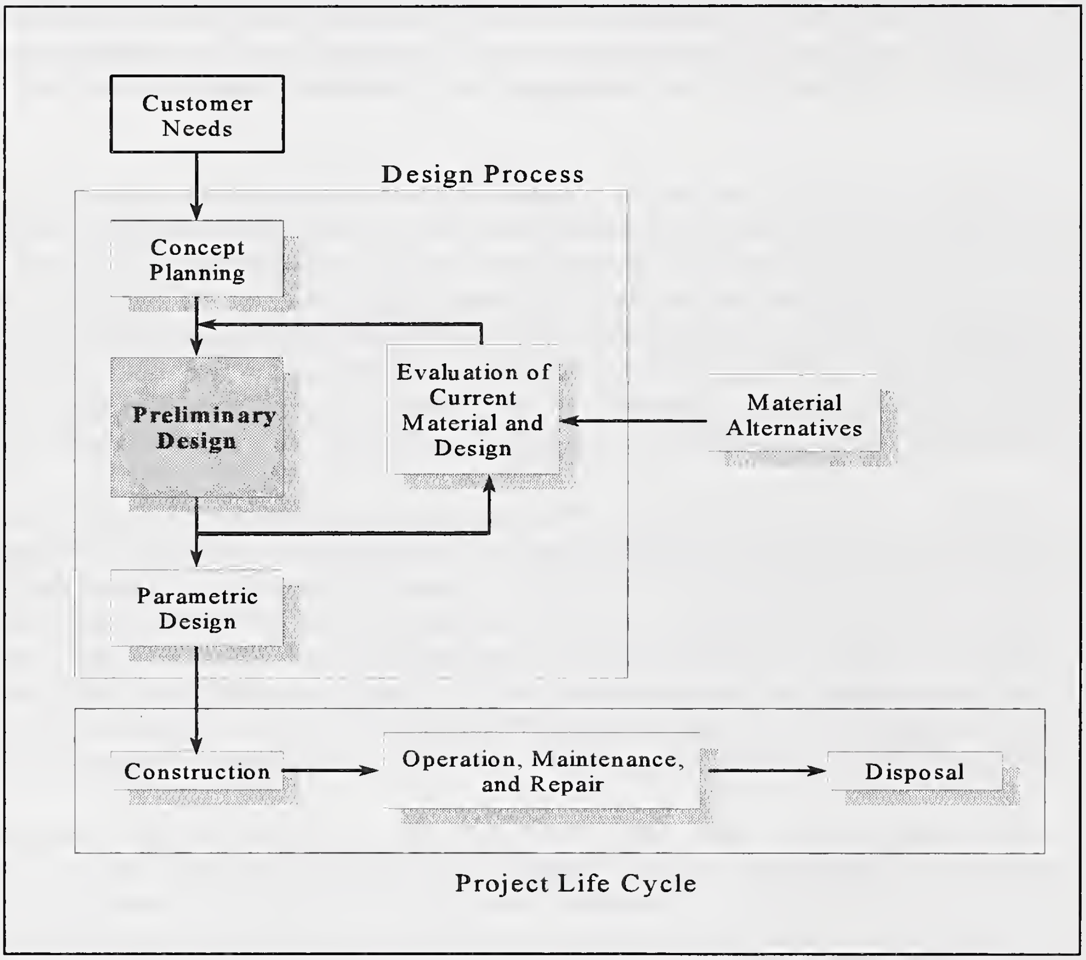

Figure 1. The Process of Designing, Building, and Using a Facility

During the Preliminary Design phase, an initial set of materials and design is proposed for the facility. This initial design is then evaluated against the set of possible material/design alternatives. But the criteria used during this evaluation often vary depending on factors such as the knowledge level of local designers and of the contractors who will build the facility. The economic criterion for choosing construction materials and design is typically lowest first cost, precluding use of a new material which might be significantly more cost effective in life-cycle terms.

To evaluate alternative building and construction materials in a consistent manner, the construction industry needs practical economic methods and guidelines. Providing such a method for determining life-cycle cost

effectiveness will give decision makers a tool to help them select, both for research and construction applications, those materials that will make firms competitive and help government agencies deliver the nation's infrastructure at minimum life-cycle cost.

1.2 Purpose and Scope

The purpose of this report is to provide a general method for evaluating the life-cycle cost effectiveness of new-technology materials in relation to conventional materials. The method provides users with a tool that helps them choose that material among competing alternative materials that performs the required function at minimum life-cycle cost. That is, the method helps the user choose the material that maximizes net present-value savings over the life of the project when compared against a material used as the base-case alternative. We provide a classification of the types of costs that characterize the use of new materials to help analysts find all of the cost elements that are appropriate for an economic analysis.

To illustrate an application of the economic method, we prepare a case study of highway bridge decks. We evaluate the use of FRP materials as an alternative to conventionally used concrete. The rapidly increasing research on FRPs suggest that it will be a major construction material in the future. We choose bridge decks for two reasons: first, this application of FRPs appears technically promising, and second, there is a large number of bridges in the United States that will need to be replaced in the next 10-15 years, suggesting that there will be considerable interest in a case study of this application.

Although the focus of the report is on construction applications of new materials, the methods presented here are equally applicable to non-construction materials and projects, or the evaluation of any capital budget expenditure as long as the performance of each competing alternative meets project requirements. These economic tools are, in part, a method for satisfying federal life-cycle cost mandates such as the Intermodal Surface Transport Efficiency Act of 1991 and Executive Order 12893's "Principles of Federal Infrastructure Investment."[4]

Note too that while we restrict the report's scope to life-cycle cost or net savings analysis, other economic methods are also useful.[5] For a description of these methods and examples of their applications in building and construction, see the ASTM compilation on Building Economics.[6]

1.3 Organization

Chapter 2 presents life-cycle cost and net-savings formulas for computing the economic worth of alternative materials. We present in detail the steps in performing a life-cycle cost analysis and the

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[4]Sections of the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) require consideration of "... the use of life-cycle cost in the design and engineering of bridges, tunnels, or pavement." The interim final rule on implementation of ISTEA management systems requires consideration of life-cycle costs in pavement and bridge management systems. Executive Order 12893, "Principles of Federal Infrastructure Investment," requires that benefits and costs of infrastructure investment "... should be measured and appropriately discounted over the full life cycle of each project."

[5]We also restrict the report's case study to deterministic analysis in which costs are quantifiable and presumed certain, and the technical performance of the alternative materials is presumed to satisfy minimum performance requirements. Chapter 4 introduces tools for further research that treat cases where multiple attributes (including non-economic and non-quantifiable attributes) are examined and where uncertainty and risk are evaluated in probabilistic terms.

[6]American Society for Testing and Materials, *ASTM Standards on Building Economics*, Third Edition, Philadelphia, PA, 1994.

requirements or rules for doing a valid life-cycle cost study. We also describe three types of decisions in project evaluation for which life-cycle cost and net savings methods are appropriate. To help analysts identify all of the cost elements that are appropriate for an economic analysis, the chapter concludes with a classification of the types of cost savings that characterize the use of new materials.

Chapter 3 presents the bridge deck case study. It begins with a rationale for considering FRP composites as a decking material. Then we present the technical and performance specifications of the case study, prototypical bridge along with a discussion of why we chose that bridge. Next is a description of the base-case deck's material and its life-cycle costs. These costs include construction, operating, maintenance and repair costs, and disposal costs, as well as user costs from redirected traffic. We then provide a similar description of material and costs for the alternative FRP decks. Chapter 3 closes with a comparison of the life-cycle costs of alternative decks and estimates of potential net savings from substituting FRP composites for conventional material decks under the assumptions of the case study. A sensitivity analysis shows how significant are the various cost items in making FRP decks economically competitive in the case study. Note that, while Chapter 3 shows circumstances under which FRPs will be the cost-effective choice for bridge decks, the intent of this chapter is *not* to make a statement about the relative cost effectiveness of the two materials. Rather, it is to *illustrate* the economic method of comparing technically promising new-technology materials vis-a-vis conventional materials.

Chapter 4 summarizes the presentation of the economic method and the bridge deck case study. Suggestions for further research on three topics related to the economics of new-technology materials complete the report.

2. Life-Cycle Cost (LCC) Model

Numerous economic models are available for evaluating new-technology materials. In the private sector, after-tax profit-and-loss models typically dictate choice. When a project has objectives that are non-quantifiable, private and public decision makers sometimes use multiattribute decision analysis to evaluate alternatives.[7] Public officials draw upon a family of economic analysis methods that measure benefits (or savings) and costs attributable to projects and project alternatives.[8] These methods help decision makers determine if a publicly-proposed project is likely to return benefits or savings that will more than cover project cost. Examples are life-cycle costing, net benefits (savings), benefit-to-cost (savings-to-investment) ratio, and adjusted internal rate of return methods.

We use a simple and flexible life-cycle cost (LCC) model in this study consistent with the standard method for performing life-cycle costing (E-917) published by the American Society for Testing and Materials. Project alternatives are material/design combinations; that is, the material being used and how it has been designed or fabricated.[9] The LCC model shows for each material/design alternative all of the relevant costs of performing a given function. The alternative that satisfies the function for the minimum LCC is the economically efficient choice, other things equal. Stated another way, the alternative that maximizes net savings (i.e., the difference in LCC) between it and the base-case alternative is the economically efficient choice. We choose the LCC model here for evaluating new-technology materials in construction because it is easy to understand; it has been federally mandated for some infrastructure projects; and it is the appropriate method when all alternatives are relatively equal in meeting the performance requirements of a project.

2.1 Formulas

2.1.1 By LCC Categories

Equation 2.1 shows the conventional cost categories included historically in the LCC model. Note that each cost category is measured in present value terms; i.e., it is converted to a common point in time (the present) so as to account for the changes in money's purchasing power over time (caused by inflation or deflation), and the real earning opportunity of money.

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[7]For a comprehensive treatment of multiattribute decision analysis techniques and how to use them, see Gregory A. Norris and Harold E. Marshall, *Multiattribute Decision Analysis Method for Evaluating Buildings and Buildings Systems*, National Institute of Standards and Technology Interagency Report 5663, September 1995. See also section 4.3.3.

[8]For a description of various economic methods for assessing the relative cost effectiveness of projects, see American Society for Testing and Materials, *ASTM Standards on Building Economics*.

[9]For example, the material concrete can be designed as poured-in-place, pretensioned, or postensioned. In our case study, we investigate three different fabrications of FRP composites: Seeman Composite Resin Infusion Molding Process (SCRIMP), wood core, and pultruded plank.

$$PVLCC = IC + PVOMR + PVD, \tag{2.1}$$

where

$PVLCC$	=	Present value of total life-cycle cost,
IC	=	Initial construction costs,[10]
$PVOMR$	=	Present value of operation, maintenance, and repair costs, and
PVD	=	Present value of disposal costs.

Initial construction costs are generated from all activities necessary to put the project into operation. These activities include parametric design, permits, surveying, furnishing and installing all physical components of the structure, contingencies for expected change orders, and final inspection. Operation, maintenance, and repair costs cover expenses necessary to operate the facility (such as utilities, security, and insurance) and to keep the facility up to performance requirements (such as periodic inspection, repairs, and replacement of structural elements). Disposal costs are all expenses associated with removal or termination of the project, net of any salvage value the facility has at the end of the study period.

2.1.2 For Calculations

Equation 2.2 shows an alternative LCC formulation that describes mathematically the discounting of future costs to present value and their summation into a single LCC number.

$$PVLCC = \sum_{t=0}^{T} \frac{C_t}{(1 + d)^t}, \tag{2.2}$$

where

C_t = the sum of all costs incurred at time t,
d = the real discount rate for converting time t costs to time 0, and
T = the number of time periods in the study period.

The unit of time used is typically the year; thus C_t is the sum of all costs that occur in year t, and T is the number of years in the study period.

2.2 Steps in Life-Cycle Cost Analysis

The recommended steps for calculating the life-cycle cost of a new-technology material vis-a-vis a conventional material are as follows:

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[10] We assume that initial costs occur during the base year of the analysis, which in this report is the present. In this case IC is in present value dollars and does not have to be converted to present value as do the other cost components.

1. **Define the project objective and minimum performance requirements**. The performance requirements of a project should be expressed in terms that do not preclude the use of a new-technology material.[11]

2. **Identify the alternatives for achieving the objective**. Each alternative must satisfy the minimum performance requirements of the project.

3. **Establish the basic assumptions for the analysis**. These assumptions include specification of the base year for the analysis, the life-cycle study period, and the real discount rate.

4. **Identify, estimate, and determine the timing of all relevant costs**. Relevant costs are those costs that will be different among alternatives. Use the classification in section 2.5 to be sure all costs are screened for inclusion. Be sure to consider all costs to direct users of the project, and any spillover costs associated with the project.

5. **Compute the LCC for each alternative** using the common data assumptions identified in step 3 and eq (2.2).

6. **Perform sensitivity analysis by recomputing the LCC for each alternative using different assumptions** about data inputs that are both relatively uncertain and significant in their impact on LCC. Sensitivity analysis shows how sensitive a technology's costs are to uncertain data used in the economic analysis.

7. **Compare the alternatives' LCCs** for each set of assumptions.

8. **Consider other project effects**—quantifiable and non-quantifiable—that are not included in the LCC calculus. If other effects are not equal and are considered significant, then turn to techniques such as multiattribute decision analysis to account for all types of benefits and costs.[12]

9. **Select the best alternative.** Where other things are equal (e.g. performance and non-quantifiable impacts) select the economically efficient alternative with the minimum LCC, i.e., the greatest net savings compared to the base-case alternative. This is the criterion of the FRP case study presented in Chapter 3.

2.3 Requirements for an LCC Analysis

When using the LCC method, you must compute the LCC of two or more alternatives to measure cost effectiveness. The alternative with the minimum LCC is the most cost-effective option. If you make one

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[11] The design of a project that has new-technology material components must often be based on a performance design code as opposed to a prescriptive design code since most new-technology materials lack a prescriptive code. The foremost performance code requirement in the FRP case study in Chapter 3—regardless of the bridge deck material used—is that the bridge be able to carry AASHTO HS-20 loads and that its deflection not exceed specific maximum span deflections under such loading.

[12] See section 4.3.3 for a discussion of multiattribute decision analysis.

of the alternatives a base case (usually the one with the lowest initial cost), you can compare the LCC of every other alternative against it to see which has the greatest net savings. The LCC and net savings approaches will both indicate the same best alternative.

Because we express future costs in our case study in constant or real dollars, we use a real discount rate in eq (2.2). This means that you do not have to worry about inflation or deflation in arriving at your streams of future costs, because you are expressing costs in dollars of constant purchasing power, fixed on a calendar reference date, that exclude inflation or deflation. The real discount rate adjusts costs for the real earning opportunities of money over time. Government agencies tend to use real discount rates and constant dollars in their analyses.

If costs spread over time are denominated in current dollars (i.e., dollars of each year's purchasing power), use a market or nominal discount rate to perform your discounting. Your market rate will be larger than the corresponding real rate (assuming there is inflation) because now you have to take into account inflation (or deflation) as well as the real earning opportunities for money over time. Private firms often favor using market discount rates and current dollar values in their analyses.

You will obtain the same LCC calculations whether you use real rates of discount with constant dollars or market rates with current dollars. You will obtain spurious results, however, if you do your analysis with current dollars and a real discount rate, or with constant dollars and a market discount rate.[13]

Use the same fixed discount rate for all alternatives in a LCC comparison. Public projects typically are mandated to use a specific rate.[14] Note that the economic viability of projects that save benefits or costs over time are very sensitive to the value of the discount rate. Figure 2 shows two significant effects that the discount rate has on present values of costs spread over time.

First, as illustrated in Figure 2, the present value of a given future cost amount decreases as the discount rate increases. For example, the present value of $1,000 ten years into the future drops from $613.91 at a discount rate of 5% (Point A) to $161.51 at a discount rate of 20% (Point B). Thus projects with cost savings spread into the future will generate larger present value net savings when evaluated with low rather than high discount rates.

Second, at any given discount rate, the farther into the future that any given amount occurs, the smaller will be its present value. Looking at the 5% discount rate line in Figure 2, $1,000 ten years out, worth $619.91 in present value (Point A), drops to a present value of $482.02 by year 15 (Point C).

Use the same study period for each alternative. The study period is the time over which the alternatives are compared. Using different study periods for different alternatives distorts the LCC measure. If project alternatives have different lives, include replacements in short-lived projects and consider the salvage value of long-lived projects to arrive at a common study period.

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[13] For more discussion of how to match the appropriate discount rate to cost streams to be discounted, see Rosalie T. Ruegg and Harold E. Marshall, *Building Economics: Theory and Practice* (New York, New York: Chapman and Hall, August 1990), pp. 142-146.

[14] The Office of Management and Budget publishes federal project discount rates in *Circular A-94*; this rate was used in the case study in Chapter 3.

Implicit in any LCC analysis is the assumption that every proposed alternative will satisfy the minimum performance requirements of the project. These requirements include structural, safety, reliability, environmental, and specific building code requirements. Exclude from LCC analysis any alternatives that fail to meet the performance specifications of the project. If an alternative satisfies performance requirements and has additional positive features that are not explicitly accounted for in the LCC analysis, then consider an alternative economic measure such as net benefits.[15]

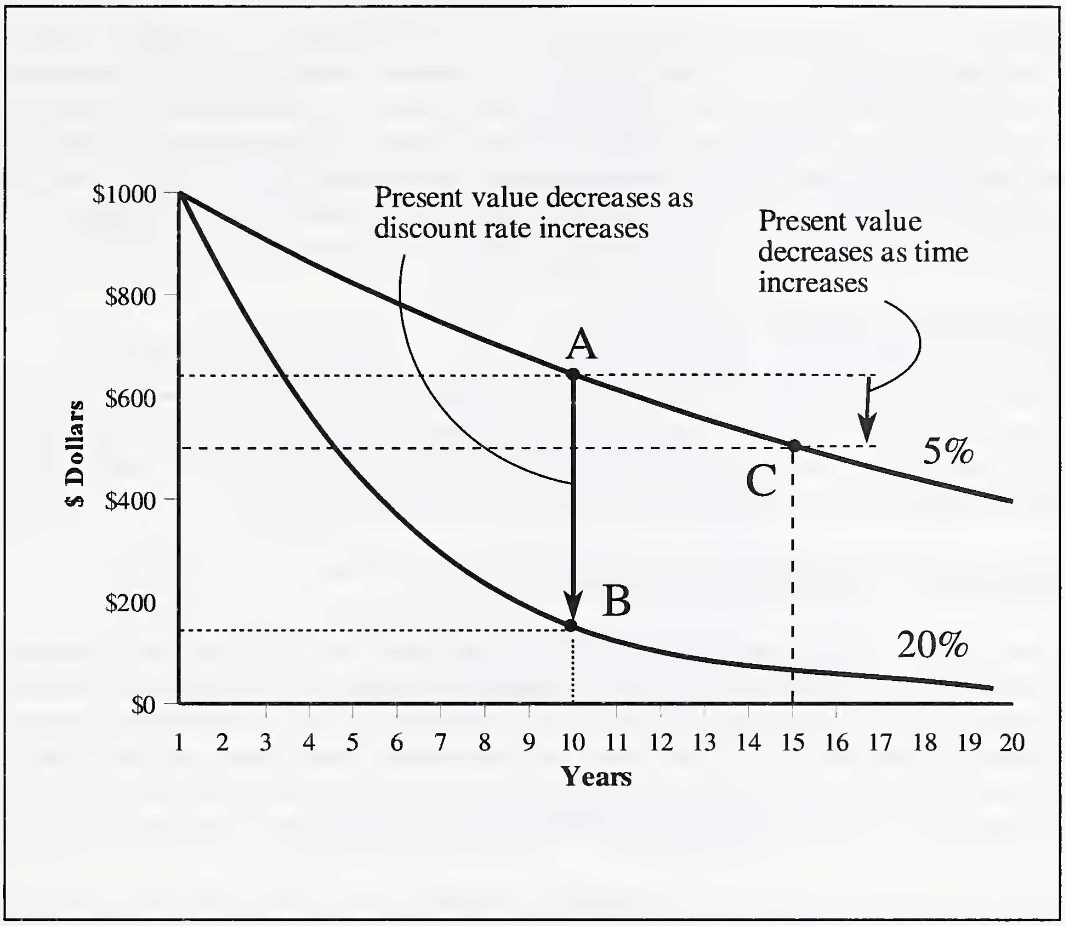

Figure 2. Present Value of Future Costs, by Discount Rate

2.4 Applications of LCC

The LCC method has multiple applications in project evaluation. We look at each in turn as it applies to construction.

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[15] For a comprehensive treatment of requirements for performing economic analyses of building and construction projects and of methods in addition to LCC, see Ruegg and Marshall, *Building Economics: Theory and Practice.*

2.4.1 Accept/Reject Decision

Choosing whether or not to do a project is an accept/reject decision. One example is deciding whether to coat an existing concrete bridge deck with polymer concrete asphalt or leave the deck "as is." The decision rule is to choose the alternative with minimum LCC.

2.4.2 Material/Design Decision

This application occurs when you must choose the most cost-effective of multiple material/design alternatives to satisfy an objective. The decision rule is to choose the material/design with minimum LCC. Choosing between FRP and concrete materials in the replacement of a bridge deck, as illustrated in Chapter 3, is an example of this type of decision. Another decision is, given a particular material, what fabrication and construction method minimizes LCC? In this application, the decision has already been made to replace the deck with a particular material; the LCC analysis is needed to decide which design is most cost effective.

2.4.3 Efficiency Level or Size Decision

Choosing how much of something to invest in is the efficiency level or size decision. An example is choosing the thickness of polymer-concrete asphalt to apply to a bridge deck. The decision rule is to choose the thickness of the coating that minimizes the LCC of the polymer-concrete road surface (where all thicknesses considered meet minimum performance requirements).

2.5 The LCC Classification Scheme

There are two primary reasons for establishing a LCC classification or taxonomy when evaluating new-technology materials. First, the classification insures that all costs associated with the project are taken into account, and that these costs are accounted for in each alternative. This includes costs incurred by the owner/operator (agency costs),[16] by direct users of the structure (user costs), and by organizations or individuals indirectly affected by the structure (spillover or third-party costs).[17] Included in these costs are unique costs relating to the introduction of new materials (new-technology introduction (NTI) costs).[18]

Second, the classification scheme allows for a detailed, consistent breakdown of the life-cycle cost and net savings estimates at several levels so that a clear picture can be had of the respective cost differences between material/design alternatives.

The classification scheme produces additional benefits such as providing a format for defining, collecting, and analyzing historical data for future projects, ensuring consistency in the data for economic evaluation of projects over time and from project to project, providing a check list for value engineering procedures, and providing a database format for computer-automated cost estimating.

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[16]We use the word *agency* here to refer to public or private agency. In the case illustration, the bridge structure is built by government agencies. For privately contracted facilities, the agency is the private firm incurring the costs.

[17]Sometimes analyses classify costs as being either *direct costs* (i.e., agency costs) or *indirect costs* (i.e., user and third-party costs).

[18]New-technology introduction (NTI) costs are those costs associated with activities that bring the new material from the research laboratory to full acceptance by the construction industry. Examples include full-scale testing and non-destructive evaluation.

The specifications of our classification scheme (Figure 3) are general enough to cover the spectrum from privately owned and operated projects to publicly owned and operated projects. The owners of some privately owned and operated structures might not include in their LCC analysis all of the user costs and spillovers that result from their projects; public agencies do not always incorporate such costs either. But environmental laws, for example, have forced private firms to internalize many spillover costs. And public agencies are beginning to treat user costs and other spillover costs as integral parts of their economic

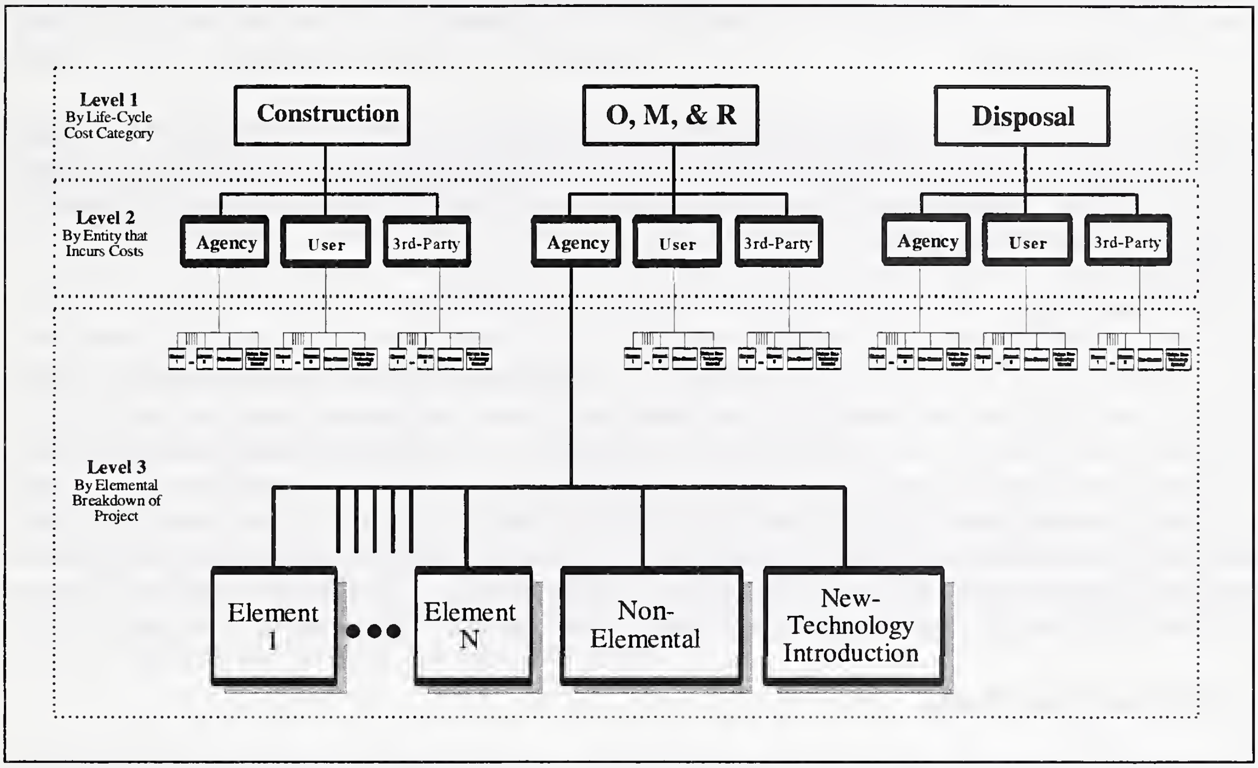

Figure 3. LCC Cost Classification

evaluations.[19] Since new-technology materials are expected to have a significant impact on user costs, and public agencies are paying increasing attention to user costs in economic evaluations, it is important to include these costs in any LCC comparison of alternative materials.

2.5.1 Costs by LCC Category (Level 1)

Figure 3 shows the three-level, hierarchical classification of costs. Summing all costs in any of the three levels yields a project's LCC. Level 1, the top row, groups costs according to the life-cycle categories

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[19] For example, Executive Order 12893, "Principles of Federal Infrastructure Investment," mandates that, with regard to direct spending or grants by the federal government for transportation, water resources, energy, and environmental protection, "... to the extent that environmental and other nonmarket benefits and costs can be quantified, they shall be given the same weight as quantifiable market benefits and costs."

typically used in the LCC formula (eq (2.1)): construction; operation, maintenance, and repair; and disposal.

2.5.2 Costs by the Entity that Bears the Cost (Level 2)

Each of the LCC categories in level 1 can naturally include agency, user and/or third-party costs. Cost components within each level 1 category, then, are next grouped by the one of these three entities that incurs the cost. Sections 2.5.2.1 through 2.5.2.3 describe these level 2 costs.

2.5.2.1 Agency Costs

Agency costs are all costs incurred by the project's owner or agent over the study period. These include but are not limited to design costs, capital costs, insurance, utilities, and servicing and repair of the facility. Agency costs are relatively easy to estimate for conventional material/designs since historical data on similar projects reveal these costs.

2.5.2.2 User Costs

User costs accrue to the direct users of the project. For example, highway construction often causes congestion and long delays for private and commercial traffic. New bridge construction impacts traffic on the highway over which it passes. Maintenance and repair of an existing bridge, along with the rerouting of traffic, can impact drivers' personal time, as well as the operating cost of vehicles sitting in traffic. Accidents, involving harm to both vehicles and human life, tend to increase in road work areas. These traffic delay costs, idle-capital costs, and accident costs can be computed using simple formulas and tabulated traffic statistics from state departments of transportation. Similar types of user costs can be computed for projects where changes to buildings or other structures directly impact occupants.

2.5.2.3 Third-Party Costs

Third-party or spillover costs are all costs incurred by entities who are neither the agency/owners themselves nor direct users of the project. One example is the lost sales for a business establishment whose customer access has been impeded by construction of the project, or whose business property has been lost through the exercise of eminent domain. A second example is cost to humans and the environment from a construction process that pollutes the water, land, or atmosphere.

We offer no models or formulas for computing these spillover costs because they are highly specific and unique for each project. For the environmental costs, some agencies will maintain that in any given project they meet environmental standards, so there are no extraordinary environmental costs beyond what is captured in the normal costs of project construction.

2.5.3 Costs by Elemental Breakdown (Level 3)

The third level of classification organizes costs (1) by specific functional element of the structure or facility, (2) by activities not assignable to functional elements (e.g., overhead), and (3) by any activities associated with the introduction of a new-technology material. Parts (1) and (2) are the traditional "elements" in an

elemental cost estimate. We add part (3) on new-technology introduction costs to measure the unique costs of using a new material. We call these three groups an elemental classification.

2.5.3.1 Elemental Costs

Elements are major components of the project's structure, and are sometimes referred to as component systems or assemblies. Major elements that are common to most buildings, for example, are the foundation, superstructure, exterior closure, roofing, and interior.[20] Elements common to bridges are superstructure, substructure, and approach. Each element performs a given function regardless of the materials used, design specified, or method of construction employed.

Individual cost estimates at the elemental level (e.g., $/square meter to furnish and install a concrete deck) are most useful in the pre-design stage when a variety of design/material combinations are being considered. This is the stage at which large net savings can be achieved by making economically optimal material/design choices. Detailed cost estimates of each alternative at the pre-design stage may not be economically feasible; elemental-based estimates, on the other hand, can be done quickly and are generally accurate enough to guide material/design decisions. Note, however, that for new-technology material/designs, there will not always be sufficient data to do element-based estimates; detailed products-based estimates and crew studies may be necessary.[21]

2.5.3.2 Non-Elemental Costs

Non-elemental costs are all costs that cannot be attributed to specific functional elements of the project. A common example of a non-elemental agency cost is overhead and profit;[22] a non-elemental third-party cost could be spillover costs. Because elemental cost categories are useful for generating and updating historical unit cost measures, all project costs that are not truly elemental must be excluded from these historical statistics and put in the non-elemental group.

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[20]Estimated costs for new construction are typically computed one of three ways: based on the products that constitute the structure (e.g., concrete, wood, reinforcing steel), based on functional elements of the facility (e.g., slab-on-grade, wall systems, roof), or based on a combination of both (e.g., estimates based on products, but categorized and sometimes estimated by functional element). For a representative products-based classification, see *MASTERFORMAT*, the Construction Specifications Institute, 1988 edition (Alexandria, VA: CSI, 1988). For a representative elemental classification of buildings and related sitework, see Brian Bowen, Robert P. Charette, and Harold E. Marshall, *UNIFORMAT II—A Recommended Classification for Building Elements and Related Sitework*, National Institute of Standards and Technology Special Publication 841, August 1992 or ASTM Standard E1557-93, *Classification for Building Elements and Related Sitework—UNIFORMAT II*, published in *ASTM Standards on Building Economics*.

The case study in Chapter 3 has both products-based estimates and elemental estimates. For example, the construction cost of the base-case concrete deck is based on the elemental estimate of $\$161/m^2$ for furnishing all labor, materials and equipment to construct the deck; the construction cost for the SCRIMP FRP deck, on the other hand, is based on the unit costs of the individual products that make up the deck: the SCRIMP FRP deck sections (plus shipping cost and on-site deck installation), elastomeric bearings, guard rails, center median, and polymer-concrete asphalt. See Appendix C for more examples of elemental and products-based estimates.

[21]The following concrete slab estimate illustrates a products-based estimate with crew study. First, tabulate and price all materials to be used for constructing the slab, including materials for formwork. Next, determine the labor hours, equipment requirements, and associated costs for excavation, forming, pouring, finishing, and then removing formwork. Sum your product costs for the final estimate. An elemental estimate for the same slab, on the other hand, is simply the cost per square meter to furnish and install the slab, including all material, labor, and equipment costs. But you must first know this cost per square meter to do the elemental estimate.

[22]In making an estimate to bid on a project, a private company will have overhead and profit included as a cost element. Profit for the contractor comprises a part of costs to the agency that contracts out the project.

2.5.3.3 New-Technology Introduction (NTI) Costs

The final category contains costs directly associated with using a new material. The costs are generated from activities that insure that the designer is satisfied with the material's performance and predicted service life. Said another way, the NTI costs cover the activities that bring the material from the research

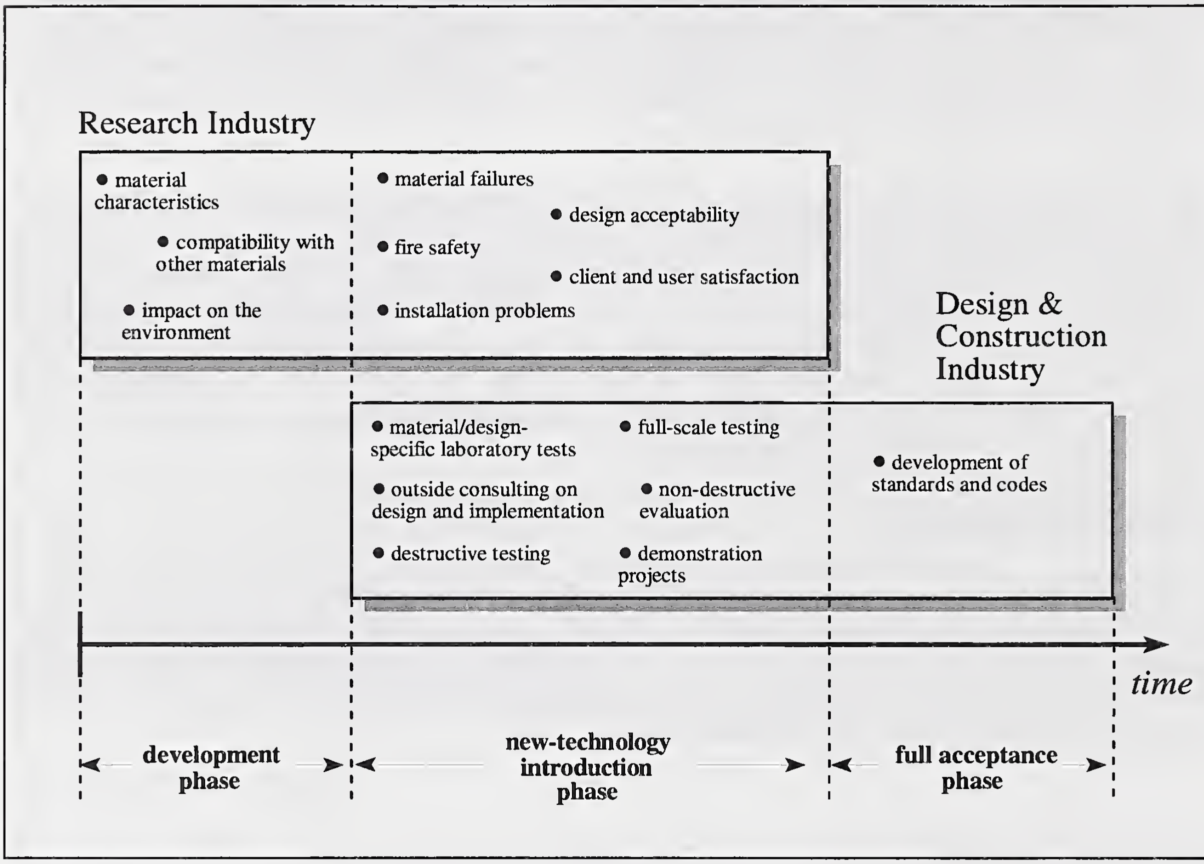

Figure 4. Evolution of New-Technology Materials

laboratory to full field implementation. Figure 4 illustrates typical activities that occur in the new-technology introduction phase.[23]

In the development phase of a new material, laboratory researchers develop an understanding of the material's properties such as its structural and corrosive behavior and corrosion resistance, and how well it performs in conjunction with other materials. If promising applications are identified, both the research and construction industries will conduct activities which introduce and integrate the new-technology material to mainstream construction. These activities will include investigating material failures and

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[23]The list of NTI-phase activities is from H. J. Rosen and P. M. Bennett, *Construction Materials Evaluation and Selection: A Systematic Approach* (New York, NY: Wiley, 1979).

installation problems and carrying out demonstration projects and non-destructive evaluation. If the material reaches full acceptance, these activities tend to diminish or stop.

New-technology introduction costs are all project-assignable costs. They include the extra time and labor to design, test, monitor, and use the new technology. These activities and costs disappear once the designer is satisfied with the technology's performance and service life, the technology enters full implementation, and its application has become routine. Examples of activities which help insure acceptability of a new-technology material and design include[24]

- Full-scale testing and other laboratory tests;
- Demonstration projects;
- Hiring consultants and/or research institutions to assist in the evaluation process;
- The training of inspection, maintenance, and repair crews in the use of the new material;
- Non-destructive monitoring and evaluation of the new structure; and
- Additional material testing for government acceptance.

The costs of these activities can be directly estimated, as we do in the case study in Chapter 3.

2.5.4 An Example of the Cost Classification Scheme

As an example of how the cost classification is used to organize an LCC estimate, Figure 5 shows a typical engineer's estimate of agency construction costs made by a state department of transportation.

Prior to public bidding of a highway overpass project, a state engineer estimates new construction costs by making a detailed quantity take-off of materials, and then assigning unit costs which reflect the labor, material, and equipment necessary to put the subcomponent materials in place. These quantity take-offs are often structured by bridge component (level 3 project elements): bridge deck (element 1), substructure (element 2), and approach roadways (element 3). Non-elemental costs and new-technology introduction costs are then estimated and grouped as separate categories of level 3 costs. Next, because these level 3 elemental costs are incurred by the state agency, they are classified as level 2 agency costs. Said another way, the sum of all level 3 construction costs is the total agency cost of construction. Finally, these level 2 agency costs (along with any level 2 user costs or third-party costs) are classified as level 1 construction costs (that is, the sum of all level 2 agency, user, and third party costs associated with new bridge construction is the total level 1 construction cost of the project).

There are at least three benefits to this LCC classification of an engineer's estimate. First, it requires little to no restructuring of how current estimates are organized. Second, it insures proper identification and placement of costs due to its top-down and bottom-up functionality. The classification insures proper identification of all construction costs by allowing the estimator to start at the top of the classification (level 1) and work his or her way down each level. The classification's bottom-up ability is equally important: any estimate of a cost can be placed properly in the LCC classification by noting which component of the

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[24]A new material also has some costs which may be difficult to compute. For example, a designer may not be as familiar with the new-technology material as with conventional materials, including properties such as tensile and compressive strength, modulus, fracture toughness, and maximum bearing pressure. This lack of knowledge could impact total project costs through higher factors of safety in design.

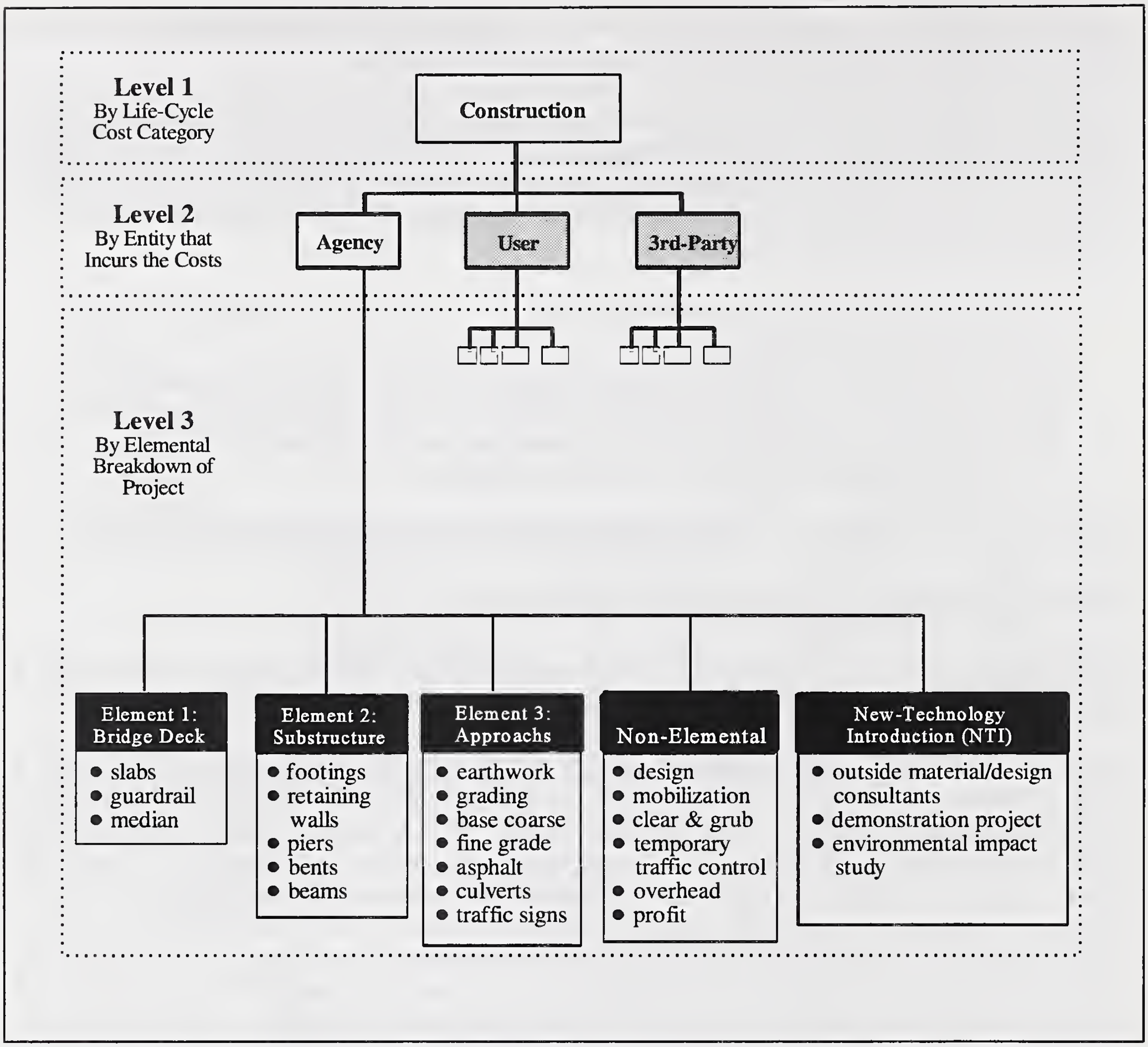

Figure 5. An Example of the Cost Classification for an Engineer's Estimate of New Bridge Construction (with NTI Costs)

project generates the cost (level 3), which entity incurs the cost (level 2), and at which point in the project's life span the cost occurs (level 1). The third benefit of this LCC classification is that actual construction costs classified by the same structural elements can be used to compile historical unit cost data on level 3 bridge element costs to be used in future LCC analyses.

3. Case Study: FRP Bridge Decks

To illustrate the life-cycle cost and new-technology material concepts of Chapter 2, we perform a detailed LCC case study of highway bridge decking. A bridge under construction in North Carolina is the case-study bridge. This bridge will provide two lanes of traffic over an existing four-lane interstate; its deck is to be made of 210.9 kg/cm^2 (3,000 psi), steel-reinforced, poured-in-place concrete. We consider three new-technology bridge deck materials—all made of an FRP material, but all fabricated differently. The life-cycle cost of each deck made from this new material is computed, along with the LCC of a base-case deck made from a conventional concrete material. Net savings comparisons are made between the concrete deck and each of the three FRP decks.

3.1 Background

Of the roughly one-half million federal highway bridges in the United States, approximately 200,000 are deficient in some capacity; between 150 and 200 bridges suffer partial or complete collapse every year. Current estimates of the cost for repairing or replacing all deficient bridges start at $90 billion.[25]

FRP composites are well positioned to satisfy part of this bridge renewal. They have been under development for over 50 years, and, as compared to steel, they are lighter, more resistant to corrosion, and can be as strong. The FRP composite industry is immense, and has evolved into two distinct tiers:

1. An *advanced-composites* tier which satisfies military, civilian aerospace, and sporting goods demand. World demand for advanced composites was $4.7 billion in 1991. Demand in the U.S. alone was $2.6 billion that same year, and given the level of anticipated military downsizing, is expected to remain at that level in the year 2000.

2. An *engineered-composites* tier which caters to consumer markets. Demand in the U.S. for engineered composites in 1991 was $10.4 billion.[26]

FRP composites have made significant in-roads in some sectors of civilian construction, itself a $400-$500 billion industry.[27] For example, underground storage tanks made of advanced composites are now the norm. Highway bridge decks are often cited as a potential application of advanced composites.

3.1.1 The Case Study Bridge

Our case study or "prototypical" bridge is currently under construction in Brunswick County, North Carolina. It is a two-lane overpass which allows traffic on NC130 to cross four lanes of US17 unimpeded. The bridge will replace the current stop-light intersection just north of the planned bridge. Figure 6 shows a plan view of the new bridge.

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[25] Kenneth F. Dunker and Basile G. Rabbat, "Why America's Bridges are Crumbling," *Scientific American*, March 1993, pp. 66-72.
[26] J. Gudas, "Manufacturing Composite Structures, Supplemental Information for Program Competition 94-02," Advanced Technology Program (Gaithersburg, MD: National Institute of Standards and Technology).
[27] *Ibid.*

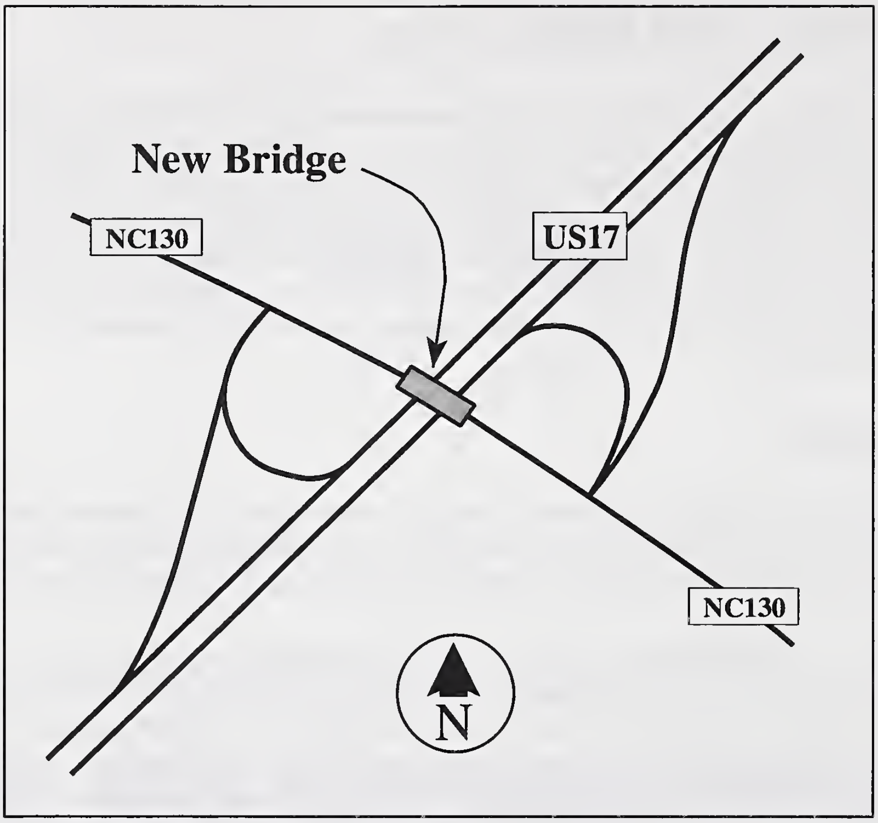

Figure 6. Plan View of Prototypical Bridge

NC130 runs in the north-west/south-east direction, while US17 runs in the south-west/north-east direction. Figure 7 shows an elevation of the prototypical bridge.

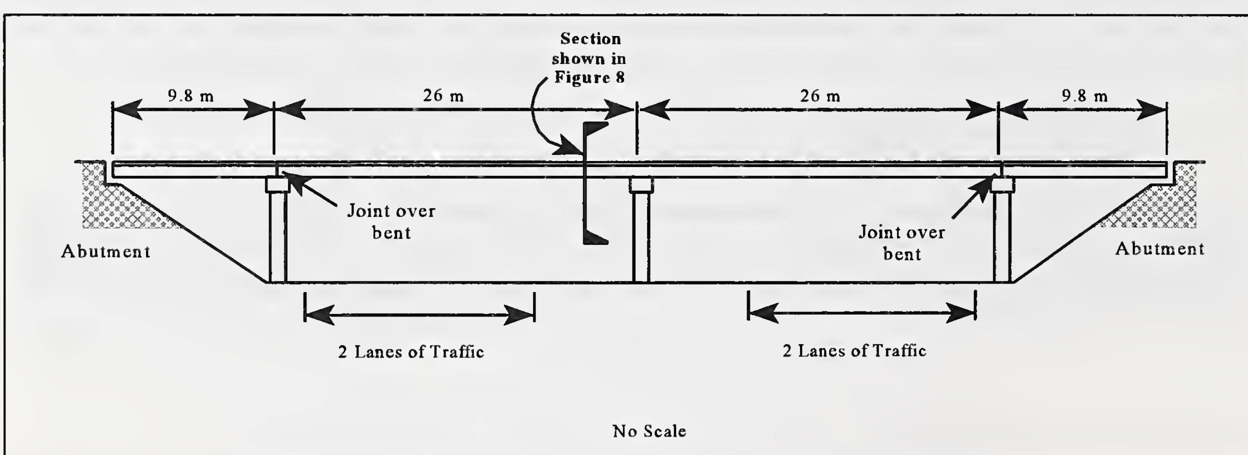

Figure 7. Elevation View of Bridge

The bridge is composed of two 26 m (86 ft) main spans directly over US17 traffic, and two 9.8 m (32 ft) spans which adjoin the main spans to the abutments. Precast, pretensioned concrete beams are placed over three reinforced concrete (RC) bents and two RC abutments. Expansion joints exist in the bridge deck, directly over the two outer bents. Figure 8 shows a typical section through one of the spans (for example, at the cut indicated to the left of the center bent in Figure 7).

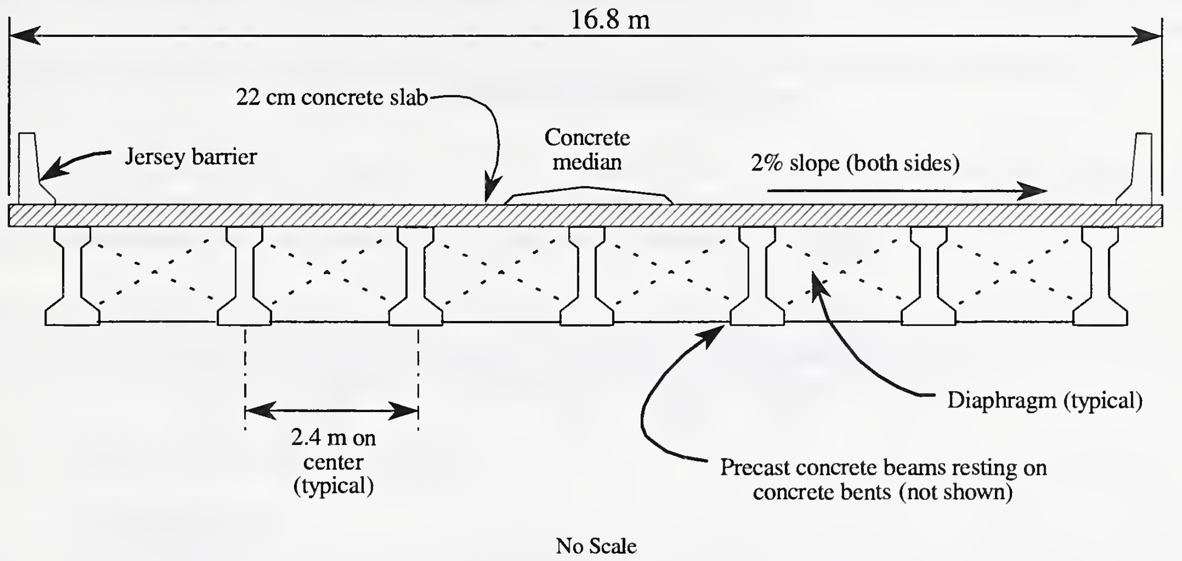

Figure 8. Section Through Bridge Span

RC diaphragms are poured to laterally support the beams. Flat metal tray forms are then placed on the beams so that the reinforcing steel can be positioned and tied, and the 22 cm (8.5 in) concrete deck can be poured and finished. After 14 days or when the concrete has achieved sufficient strength (whichever comes first), RC Jersey barriers are formed and poured along both edges of the bridge deck to prevent overpass traffic from driving off the edge of the bridge.

3.1.2 Design Implications for Cost

The life-cycle cost of a structure is not only a function of its materials, but of how the materials are designed to be used. Said another way, it is the material/design combination which determines life-cycle cost. Bridge decks are not an exception. For example, the material requirements and life-cycle performance of a bridge deck are functions of whether or not the deck is constructed with the beams as a monolithic assembly to resist bending in the long spans between supports. Figure 9 illustrates the structural

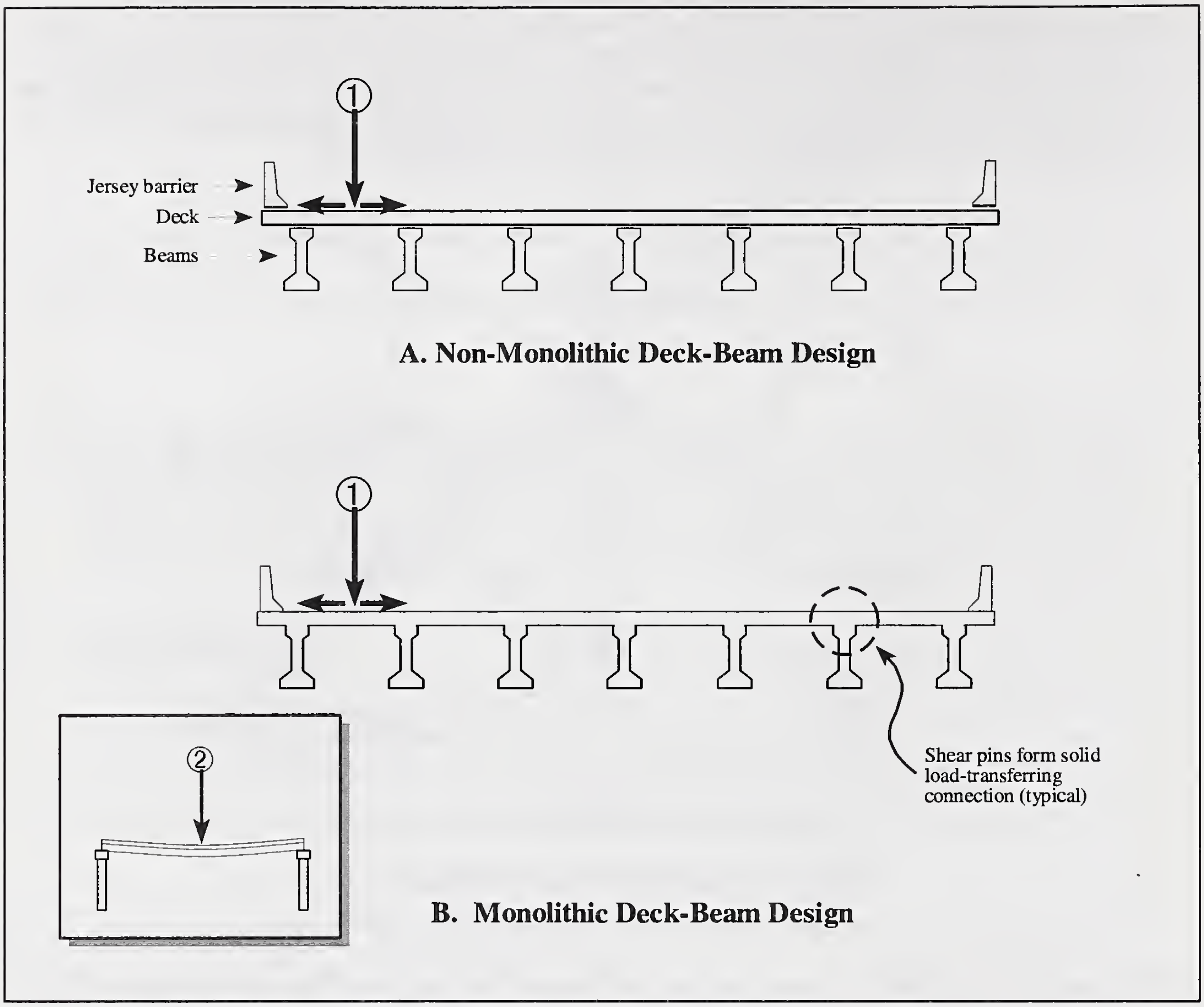

Figure 9. A Comparison of Monolithic Deck-Beam and Non-Monolithic Deck-Beam Designs

differences between a deck-beam assembly constructed monolithically and a deck-beam assembly which is not monolithic.[28]

Bridge decks can serve two primary structural functions. The first function of a deck is to transfer loads which occur between the beams to the beams themselves (indicated by "①"). The second deck function is to act in a combined manner with the beams to resist bending in the spans between supports (indicated by "②").

[28] The monolithic deck-beam is often called a "composite deck-beam," but we use the term monolithic to avoid confusion with the FRP composite construction material.

The monolithic deck-beam design is a superior design for concrete decks in that the monolithic deck-beam assembly can carry more load than a non-monolithic assembly of the same size and materials. The same may not be true, however, for new-technology materials like FRP composites. Because a structural member made of FRP composites may often be stronger and stiffer than a comparable member made of conventional materials, less FRP material is needed.[29] If composites are chosen as the deck material in a monolithic deck-beam design, this reduction in deck material may cause stresses in the shear pin connections (indicated by the dotted circle in Figure 9) that exceed the allowable stresses of the FRP material. If the FRP composite deck is not designed to act in a combined manner with the beams to resist bending, but rather to only transfer between-beam loads to the beams themselves (and the beams are strengthened to offset this reduced between-pier carrying capacity), these excessive shear stresses can be avoided.

The implication is that FRP composites may not be cost effective when based on a conventional-material design. While up-front redesign of the bridge may be required when using a new-technology material, this redesign is possible and may make the new construction material cost effective.

These design-based cost implications are illustrated in our case study. The life-cycle costs of the reinforced concrete deck and SCRIMP FRP deck are based on a monolithic deck-beam design, while the LCCs of the wood-core and pultruded-plank decks are based on non-monolithic deck-beam designs.

3.2 Life-Cycle Cost Analysis

We now summarize the life-cycle cost comparisons of concrete bridge decks and new-technology material decks.[30] This comparison follows the LCC methodology in section 2.2 and cost classification outlined in section 2.5. In particular, note that we include user costs and any costs directly attributable to the introduction of a new material. This LCC framework is equally useful for comparing other decking materials such as high-performance concrete, steel grids, aluminum, and wood.

Our project objective is to provide a bridge deck for the new NC130-US17 bridge in Brunswick County, North Carolina. This includes the installation, inspection, maintenance and repair, and disposal of the deck. Project performance requirements include satisfying AASHTO HS20 minimum load requirements.[31]

Our base-case material/design is poured-in-place reinforced concrete as specified in the construction drawings. The three new-technology material alternatives are all made of FRP composites but have significantly different fabrication techniques. Figure 10 summarizes this material/design breakdown.

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[29] For example, the SCRIMP FRP deck in the case study in Chapter 3 has the same depth (22 cm) as the base-case concrete deck, but one-sixth the cross-sectional area of structural material. See Figures 11 and 12 to compare the cross-sectional composition of the concrete and SCRIMP decks.

[30] For a complete breakdown of estimated costs, see Appendix C.

[31] There may be other factors which affect the design of a bridge such as land on which it is built, or the angle of the bridge relative to traffic flow under the bridge. We assume for this case study that these factors have the same effect on the design of both reinforced concrete and FRP decks. Whenever design requirements are significant with respect to costs among design/material types, consider the implications of the additional design requirements to make the LCC calculations more precise.

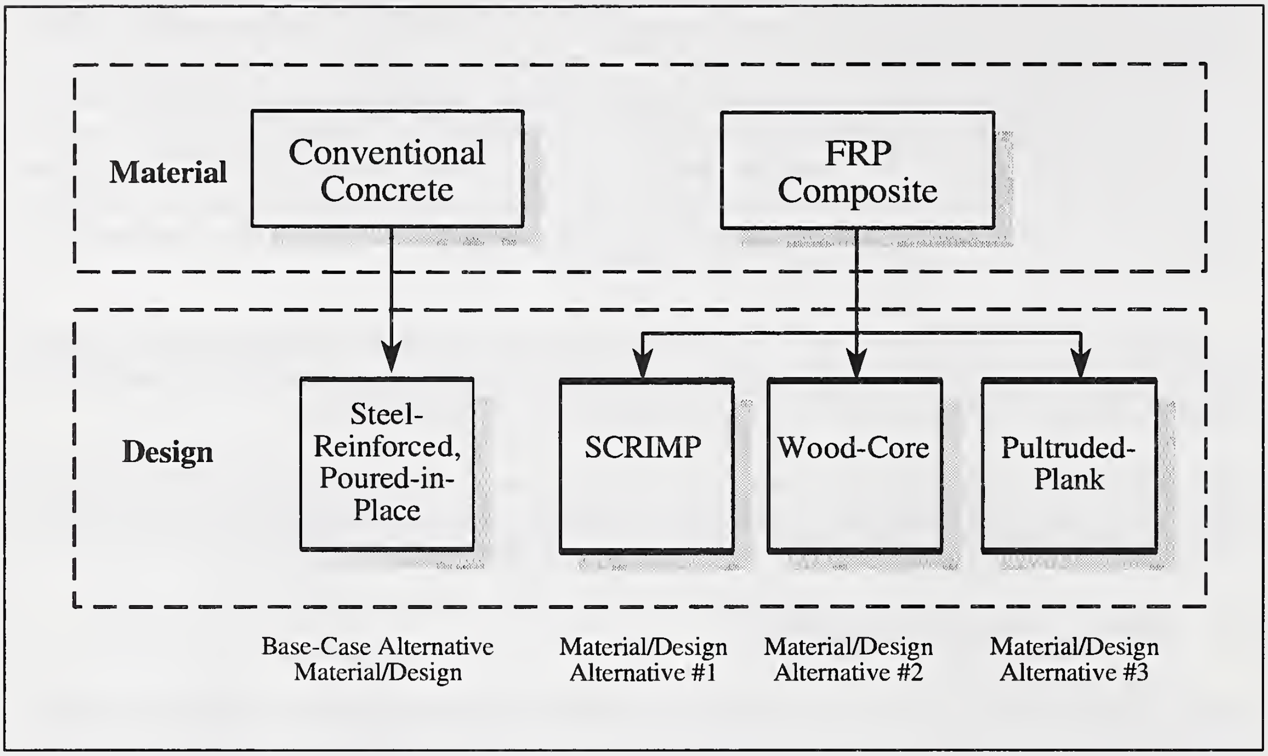

Figure 10. Case Study Material/Design Alternatives

We use LCC and Net Savings methods to compare three FRP decks to a base-case, conventional concrete deck. The concrete deck design is that described earlier in section 3.1.1. The FRP decks are:[32]

1. *SCRIMP (Seeman Composite Resin Infusion Molding Process)*: This is one form of vacuum-assisted resin transfer molding. E-glass fabric is laid in its final design configuration using a foam core and an external mold. Resin is then pulled through the cavities using vacuum pressure. Once the resin sets, the mold is removed. The foam remains as a permanent but non-structural part of the deck.

2. *Wood-Core Sandwich*: Vertical Asian structural bamboo sections are assembled into a rigid "sandwich" core. The top, bottom, and sides are then covered with layers of fiberglass, and resin applied.

3. *Pultruded Plank*: Lineal planks are pultruded from resin-wetted fiberglass fabric and fiberglass strand. Once individual planks have set, three sections are then joined at their sides with key strips to form a wider cross-section.

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[32] For detailed drawings of the base-case and alternative material/design alternations, see Figures 11-14.

The following assumptions were common to all four material/design combinations:

1. The intended service life of the bridge is 40 years (specified by the North Carolina Department of Transportation (NCDOT)), so the LCC study period is set at 40 years.
2. The real discount rate for computing the present value of all future costs is 3.0% (This is based on OMB Circular No. A-94, Appendix C, Revised February 1996).
3. Length of highway affected by bridge construction, maintenance, and disposal: 1 mile each for NC130 and US17 (estimated from project drawings).
4. Average Daily Traffic (ADT) figures: based on NCDOT forecasts recorded on project drawings.
5. Normal driving speeds for NC130 and US17: 45 mph and 55 mph (NCDOT).
6. Average driving speeds on NC130 and US17 during bridge work: 35 mph (NCDOT).
7. Normal accident rate (per million-vehicle-miles): 1.9 (California Department of Transportation (CALTRANS)).
8. Accident rate in road work areas (per million-vehicle-miles): 2.2 (CALTRANS).
9. Hourly value to drivers of delay: $10.73/hr (CALTRANS (1995)).
10. Hourly vehicle operating cost: $8.85/hr (CALTRANS (1995)).
11. Average cost per accident: $103,781 (CALTRANS (1995)).

The life-cycle cost of each alternative is estimated using the LCC classification scheme (section 2.5) and a top-down approach. Level 1 categories estimated are Initial Construction; Operation, Maintenance, and Repair; and Disposal. For each level 1 category, level 2 Agency and User costs are computed. Third-Party costs are not estimated; these costs can be significant in urban areas—such as lost sales to businesses that have been made partially or totally inaccessible by the roadwork—but are insignificant in our case study due to the remoteness of the overpass and the provisions that the NCDOT made to minimize project impacts on businesses and residences in the surrounding area. For each level 2 category, we estimate level 3 Elemental and New-Technology Introduction costs. Our project's elemental structure has only a single element, the deck.[33]

3.2.1 LCC of Reinforced Concrete Deck

The NCDOT drawings call for a 22 cm (8.5 in) concrete slab to be poured over prestressed concrete beams, themselves placed 2.4 m (8 ft) on center. Figure 11 shows a schematic of a typical reinforced concrete deck. Reinforcing steel runs both longitudinally and transversely to the flow of bridge traffic.

The deck is sloped 2% away from the center median so that rainwater doesn't collect on the bridge (see Figure 8). Joints in the deck exist over the two outside bridge piers and over the abutments; no joints exist in the direction of bridge traffic flow. The concrete Jersey barriers at each edge are attached to the deck via protruding reinforcing steel, and are positioned on a portion of the deck that cantilevers out beyond the

[33] If our project were an entire bridge, we could divide the structure into a number of structural components useful for organizing take-offs, as well as for generating historical unit costs for future estimates. An example of an elemental breakdown is Superstructure, Deck, Substructure, and Approaches. See the Federal Highway Administration, *Pontis Version 2.0 Users Manual*, Publication No. FHWA-SA-93-083, December 1993, for a list of bridge elements used by PONTIS, a computer bridge management system.

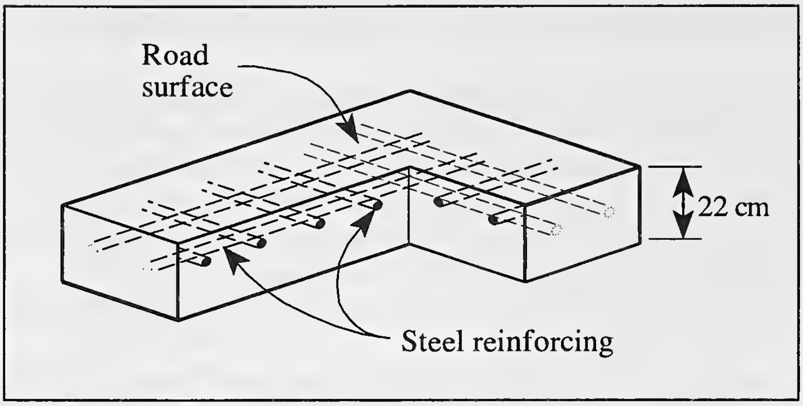

Figure 11. Reinforced Concrete Deck

outermost beams. The beams themselves have a roughened top surface and metal hooks protruding at intervals so that a strong bond will form between beam and deck. This allows the deck and beams to act as a monolithic deck-beam assembly (Figure 9). Required concrete strength is 210.9 kg/cm^2 (3,000 psi), expected to be achieved after 14 days of cure time.

3.2.1.1 Level 1 Initial Construction Costs

Construction of the deck starts with installation of wooden false work to the beams so that the beams can be prepped for deck form work. Polymer shims are placed on the beams' top edges to correct for irregularities. Metal trays are then placed between the beams to act as the concrete slab's bottom form. Bare reinforcing steel is then placed and tied on intervals, both in the direction of and orthogonal to bridge traffic. The concrete is then poured and the top surface finished; it then must cure for either 14 days or until samples indicate that sufficient strength has been reached. After this cure time, the Jersey barriers and concrete center median are formed, poured, and stripped.

Following the LCC cost classification in Figure 3, Level 1 construction costs are the sum of all agency, user and third-party costs that occur during construction. We estimate the level 2 costs to the agency by summing all level 3 elemental costs. We allocate to level 3 elemental costs the cost to form, pour, and finish the concrete deck and barriers. This cost is estimated to be \$161.40 per m^2 (\$15 per ft^2) or \$195,000, based on historical records the NCDOT keeps for budgeting purposes.[34] Non-elemental costs such as overhead or mobilization are not accounted for because (1) the NCDOT does not have them, and (2) these costs are assumed identical across all material/design alternatives and are therefore not necessary for an LCC analysis. There are no new-technology introduction costs for the conventional concrete deck. All initial construction costs occur in the first year of the study period and so are already in present value terms.

We next compute level 2 user costs for drivers on and under the bridge, following the methodology of CALTRANS (1995).[35] Total user costs are calculated as the sum of

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[34]This was verified by discussions with the subcontractor charged with actually constructing the deck.
[35]CALTRANS, DOTP - Transportation Economics. *Life-Cycle Benefit/Cost Analysis (Highway Projects)*, 1995.

driver delay costs - the personal cost to drivers who are delayed by roadwork;
vehicle operating costs - the capital costs of vehicles which are delayed by roadwork; and
accident costs - the cost of damage to vehicles and humans due to roadwork.

Equation 3.1 is used to compute the cost to drivers of roadwork-related traffic delays.

$$\text{Travel Delay Costs} = \left(\frac{L}{S_a} - \frac{L}{S_n} \right) \times ADT \times N \times w, \tag{3.1}$$

where[36]

L is the length of affected roadway or which cars drive,
S_a is the traffic speed during bridge work activity,
S_n is the normal traffic speed,
ADT as the average daily traffic, measured in number of cars per day,
N as the number of days of road work, and
w as the hourly time value of drivers.

The time required to construct the deck (N) is 21 days.[37] The hourly value w is computed as a weighted average of commercial and personal driver hourly time values using an average truck-to-auto ratio listed on project drawings.

Vehicle operating costs are calculated using eq (3.2).

$$\text{Vehicle Operating Costs} = \left(\frac{L}{S_a} - \frac{L}{S_n} \right) \times ADT \times N \times r, \tag{3.2}$$

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[36]The difference $\left(\frac{L}{S_a} - \frac{L}{S_n} \right)$ is the additional time an individual driver must spend in traffic because of bridge work. It is derived as follows. The time that each car spends on a highway section of length L where roadwork is occurring is the number of roadwork kilometers divided by the speed of each car:

$$(L \text{ kilometers}) \div (S_a \text{kilometers per hour}) = \left(\frac{L \text{ kilometers}}{} \right) \left(\frac{\text{hour}}{\text{S}_\text{a} \text{ kilometers}} \right) = \frac{L}{S_a} \text{ hours.}$$

Similarly, the time spent on the same portion of roadway when there isn't roadwork is

$$(L \text{ kilometers}) \div (S_n \text{kilometers per hour}) = \left(\frac{L \text{ kilometers}}{} \right) \left(\frac{\text{hour}}{\text{S}_\text{n} \text{ kilometers}} \right) = \frac{L}{S_n} \text{ hours.}$$

The additional time then that each person spends driving when road work occurs is $\left(\frac{L}{S_a} - \frac{L}{S_n} \right)$.

[37]As in the case of the FRP decks, these are critical-path days. That is, any change in the number of days required to construct the deck changes the total number of project construction days by the same amount. Otherwise, reducing the number of days to construct the deck may not decrease the number of days of roadwork.

where r is a weighted-average vehicle cost based on the ratio of commercial vehicles to personal automobiles (listed on project drawings), and the other parameters are the same as those in eq (3.1).

Accident costs are calculated using eq (3.3).

$$\text{Accident Costs} = L \times ADT \times N \times (A_a - A_n) \times c_a, \tag{3.3}$$

where c_a is the cost per accident, A_a and A_n are the during-construction and normal accident rates per vehicle-kilometer, and the other parameters are the same as those listed in eqs (3.1) and (3.2).[38]

We do not include any third-party costs in the level 2 category since they were not shown to be significant in our case study. We emphasize, however, that in general the social costs of bridge construction include third-party costs, and where these costs are significant (such as in urban areas), total economic costs will be underestimated unless third-party costs are included.

3.2.1.2 Level 1 Operation, Maintenance, and Repair (OM&R) Costs

Level 2 agency operation, maintenance, and repair (OM&R) costs are based on biannual inspection of the bridge deck, supplemental inspection when necessary, and repatching of spawled portions of the road surface. Bridge decks (along with the rest of the bridge) are typically inspected every two years for damage, decay, and other signs of deficiency.[39] The NCDOT maintenance division estimates that a standard inspection takes two people one day per bridge or $100 per inspection.[40]

If damage is significant, a supplemental, more expensive inspection is called for; this may include taking core samples of the concrete deck and superstructure, and measuring the integrity of reinforcing steel-concrete interfaces. It is estimated that this supplemental inspection will occur after 25 years of bridge deck use. The supplemental inspection takes two days and the NCDOT maintenance division estimates this cost to be $500 per bridge.

Anticipated repair of the deck occurs after 28 years, when portions of the deck have spalled or cracked. Every three years (i.e., Years 28, 31, 34 and 37 of the forty-year study period), 2.5% of the deck's surface is repatched: the damaged areas are chipped away and removed of oil and dirt, and new concrete is patched

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[38]The expected number of accidents to occur during road work is

$$\left(\frac{\text{road work kilometers driven}}{\text{vehicle}}\right) \times \left(\frac{\#\,\text{vehicles}}{\text{day}}\right) \times \left(\#\,\text{project days}\right) \times \left(\frac{\#\,\text{accident vehicles}}{\text{vehicle kilometers}}\right)$$

$$= L \times ADT \times N \times A_a,$$

where A_a is the estimated number of vehicles to be involved in accidents (for every vehicle-kilometer driven). If the expected number of accidents during normal traffic flow equals $L \times ADT \times N \times A_n$, then the *increase* in accidents which is attributable to roadwork is $L \times ADT \times N \times (A_a - A_n)$, and the increased accident cost due to roadwork is eq (3.3).

[39]This is, in part, a consequence of the Federal-Aid Highway Act of 1968, which mandated both national bridge inspection standards and training for bridge inspectors.

[40]This estimate and all subsequent cost estimates are in 1996 dollars.

in place. The NCDOT road maintenance division keeps figures on the unit cost to patch decks: at \$215.20/m^2 (\$20/sf) to patch, the total cost for each repair job is (2.5%)×(1207.7 m^2)×(\$215.20/m^2) = \$6,500 in 1996 dollars.

Level 2 user costs during maintenance and repair are also computed using eqs (3.1), (3.2), and (3.3). The equations' parameters are the same as for initial construction, except that the affected roadway length is .8 km (½ mile) and the number of work days is 1 for the biannual required inspection, and 2 work days for the supplemental inspection. User costs due to repatching are only calculated for drivers on NC130: length of affected roadway is .8 km (½ mile), and patching takes three days.

3.2.1.3 Level 1 Disposal Costs

The final level 1, life-cycle cost category is disposal. The deck is removed by crushing the deck with a hydraulic pincher and then hauling off the debris. Concrete bridge decks do not have salvage value, so disposal costs are simply the cost to destroy and deposit at a landfill. Agency disposal costs are based on NCDOT historical unit costs. Since we know the cost of a new deck is \$161.4/m^2 (\$15/sf), we figure the cost difference between a deck replacement at \$322.80/m^2(\$30/sf) and a new deck at \$161.4/m^2 (\$15/sf) is the cost of disposal (i.e., \$322.80/m^2 - \$161.4/m^2 = \$161.4/m^2). This seems reasonable in that disposal is disjointed from building the new deck; i.e. disposal precedes building the replacement deck. Thus the cost of deck disposal is estimated to be \$161.40/m^2 or \$195,000. User disposal costs are based on 10 days of disrupted traffic over 1.6 km of highway on both NC130 and US17, and again are calculated using eqs (3.1), (3.2), and (3.3).

This completes the life-cycle costs for the conventional bridge deck. Equation (2.2) is used to compute the total present value LCC. Table 1 gives a breakdown of this total by level 1 and level 2 cost categories. Appendix C tabulates all of these individual life-cycle costs by level, and lists the years in which these costs occur.

3.2.2 LCC of SCRIMP FRP Deck

SCRIMP as a fabrication process can be tailored to a wide variety of final shapes with varying strengths. It has been used to fabricate boat dock fenders and insulated railroad car shells, and to wrap structurally deficient concrete columns. Figure 12 shows a schematic of the SCRIMP deck design used in the proposed alternative deck.

Table 1. Life-Cycle Cost of Reinforced Concrete Deck

Level 1/Level 2 Cost Categories	Per M^2	Per Ft^2	Total
Construction			
Agency Costs	$161.40	$15.00	$195,000
User Costs	$25.07	$2.33	$30,327
Total Construction	**$186.47**	**$17.33**	**$225,327**
Operation, Maintenance, & Repair			
Agency Costs	$7.96	$0.74	$9,640
User Costs	$29.05	$2.70	$35,051
Total Operation, Maintenance, & Repair	**$37.01**	**$3.44**	**$44,691**
Disposal			
Agency Costs	$51.00	$4.74	$61,572
User Costs	$11.41	$1.06	$13,784
Total Disposal	**$62.41**	**$5.80**	**$75,356**
Grand Total Life-Cycle Cost	**$285.89**	**$26.57**	**$345,374**
Remark: Total Agency Costs	$220.36	$20.48	$266,212
Remark: Total User Costs	$65.53	$6.09	$79,162

Note: All figures are listed in present-value dollars.

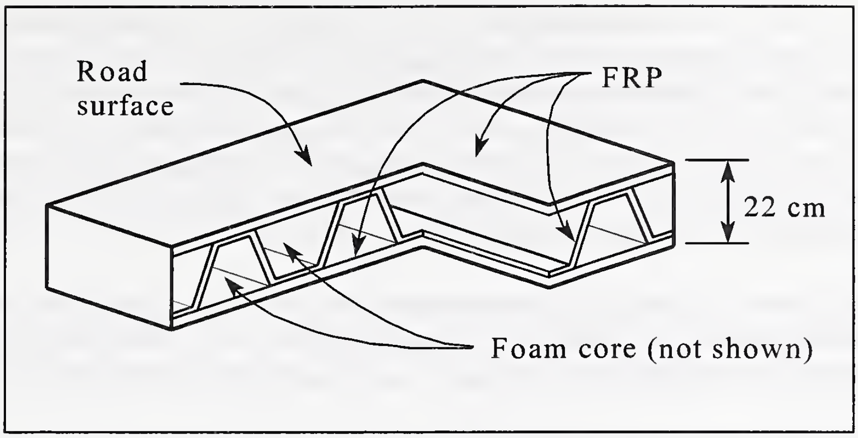

Figure 12. SCRIMP FRP Deck Material

In cross-section it is a sandwich of 9 layers of e-glass, stitch-bonded fiberglass over a five-glass-layer, trapezoidal, inner sandwich over 13 additional layers of stitch-bonded fiberglass. The voids between trapezoids and the top and bottom layers are filled with foam to aid in the fabric setting and resin transfer process. Once the top, bottom, and sides are formed, vinyl ester is dispersed through the fabric using vacuum pressure. The final deck material is 22 cm (8.5 in) thick and satisfies AASHTO HS20 load requirements, but has one-sixth of the weight of the base-case concrete deck.[41]

On site, the concrete beams are prepped for deck placement by first applying an elastomeric bearing along the beams' top edge to prevent excessive localized loads at beam-deck connections. The SCRIMP deck units are attached to the beams with shear pins. The panels are also attached to one another with long rods running perpendicular to the direction of on-bridge traffic. Three-rail steel guardrails are then fastened along both edges in lieu of Jersey barriers,[42] and a concrete center median is installed (as per the NCDOT construction drawings). Finally, a 2 cm (¾ in) polymer-concrete road surface is applied to the SCRIMP surface.

The life-cycle costs for this alternative case are also organized and estimated using the LCC classification (see Figure 3). The major cost category difference between the concrete deck and the FRP composite decks is the inclusion of new-technology introduction (NTI) costs in our estimate of FRP life-cycle costs.

3.2.2.1 Level 1 Initial Construction Costs

Level 1 initial construction costs (see Figure 3) cover all activities necessary to design and build the SCRIMP deck. The agency's elemental costs (level 3) under the initial construction category are estimated by first contacting the manufacturer for a budget price to fabricate the deck. Shipping costs from fabricator

[41] Since the SCRIMP deck also has one-sixth the cross-sectional area of the reinforced-concrete deck, there is a significant drop in the deck's contribution to FRP beam-deck bending resistance. Still, adequate moment resistance is achieved with the SCRIMP deck.

[42] These 3-rail metal barriers have been statically and dynamically tested by at least one state DOT (Michigan). We augment these barriers with a continuous metal base for installation to the FRP deck. The purpose of the metal base is to distribute loads experienced by the guard rail across a wider area of FRP deck than the area necessary for connecting the same rail to a concrete deck.

to the NC130/US17 site are based on the kilograms of deck shipped and the distance between the shop and the bridge site.[43] We use the same elastomeric bearing price as for the concrete deck since the same type and quantity of material would be used for the SCRIMP deck. Labor-hours to install the bearings and deck are the manufacturer's estimate. The metal guard rail cost came from the Michigan DOT (which uses this rail often). The budget price to furnish and install the concrete median came from the subcontractor awarded the contract to furnish & install the actual NC130/US17 deck. Polymer-concrete prices were furnished by the Virginia Transportation Research Institute.[44]

There were no non-elemental agency costs of construction, but we did estimate agency NTI costs, based on discussions with the West Virginia DOT which is building a bridge with a SCRIMP deck.[45] The agency in our case study performs the following activities to design and build the SCRIMP deck:

- outline SCRIMP research project scope;
- contract with consultants (academic and/or private sector) for SCRIMP deck design;
- run or manage material tests on deck design;
- meet with fabricator, approve final blueprints and shop drawings; and
- outline field engineering and construction inspection plan for SCRIMP deck.

Total NTI cost to the DOT/agency is the sum of DOT man-hours times an average hourly rate, plus the dollar value of all outside contracts to research facilities and/or engineering consulting firms.

Initial construction user costs of $18,744 were calculated using the same parameter values as for the base-case concrete deck, but with a roadwork schedule of 13 days. Driver delay, vehicle operating, and accident costs due to construction were again computed using eqs. (3.1), (3.2), and (3.3).

3.2.2.2 Level 1 Operation, Maintenance, and Repair Costs

Level 1 operation, maintenance, and repair costs are fundamentally difficult to estimate since the material is new. Even given the extensive FRP research done in defense and aerospace industries over the past 30 years, the actual life span of a SCRIMP bridge deck that is subject to static and dynamic vehicle loading and corrosive elements of the environment is difficult to determine. But because the failure modes of the FRP material are understood to a degree, these can be used to develop repair procedures and associated costs.[46]

We estimate level 2 agency operation, maintenance, and repair costs as the cost necessary to prevent ultraviolet radiation and moisture from shortening the deck's life span to less than 40 years, and to repair

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[43] This distance was made the same for all three FRP composites.

[44] Source: Interview with Michael Sprinkle, Virginia Transportation Research Institute. Square-yard prices are based on current contract prices for applying the polymer concrete to existing concrete decks.

[45] Dr. Hota Gangarao of West Virginia University, the West Virginia Department of Transportation, and Hard Core Dupont, Inc., are designing the new Wick Wire Run bridge as a FRP deck-beam bridge. A SCRIMP FRP deck will be fastened to steel stringers. The activities and costs listed here are patterned after the new-technology material activities they will be performing to insure design acceptability and safety. These new-technology material activities are also based on discussions with Phil Underwood of Lockheed Martin, which has developed and built an FRP composite deck-beam.

[46] Life-cycle cost tools exist for dealing with uncertainty in cost and life spans. See section 4.3.1 for discussion.

spalling of the polymer-concrete road surface.[47] The bridge will be visually inspected every two years as per current requirements. Inspectors will look for flaked paint or scratches which have exposed bare resin to sunlight or excessive moisture and mechanical wearing. Damaged resin is removed and a new protective coat applied. In Year 25 a detailed supplementary inspection similar to that for the concrete deck is done. Maintenance and repair requirements for the polymer-concrete road surface are based on life spans and repair costs obtained from the Virginia Transportation Research Council, assuming that polymer concrete attached to the SCRIMP deck will wear at the same rate it does when attached to a concrete deck.

Operation, maintenance, and repair costs to the agency due to the introduction of the new-technology material are based on discussions with the West Virginia DOT, which is currently designing and building a SCRIMP-deck bridge. These one-time costs associated with using SCRIMP for the first time include

- development of a non-destructive evaluation (NDE) plan for monitoring the deck, and
- inspecting the deck once a month for the first year, then once every six months for the next three years.

Development of the NDE plan is estimated at 100 labor-hours every year for the first four years, and each inspection would take 28 labor-hours (2 persons for 2 days). Level 2 user costs are again based on eqs (3.1), (3.2), and (3.3), using 1 day per bridge inspection, 2 days per supplemental inspection, and 2 days for repair of the polymer concrete deck.

3.2.2.3 Level 1 Disposal Costs

The reduced amount of composite material in the SCRIMP decks' cross-section significantly reduces level 1 disposal costs. Hand labor can disassemble the deck. The SCRIMP manufacturer estimated labor costs and project duration at 300 labor-hours and 2 days. Dumping fees are based on volume of deck and distance to the dump site. User costs are calculated the usual way, but with a roadwork duration of 2 days.

Table 2 lists the total LCC, as well as its breakdown by level 1 and level 2 categories. Appendix C tabulates all life-cycle costs for the SCRIMP deck and the years in which they occur.

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[47] We are not including the probability of a partial or total bridge collapse for the following reasons. First, bridge design requirements include not only minimum load capacities but also maximum deflection limits. In all three FRP deck designs, the deflection requirement was the binding requirement and drove design. The resulting strength of the FRP decks was often twice the level of required strength, implying that the decks will not fail due to overloading. Secondly, the bridge deck's exposure to cyclical loading and/or moisture could cause separation of the fabric and resin, degrading the FRPs strength, but this would result in noticeable deflections which would be detected during inspection, and remedied.

Table 2. Life-Cycle Cost of SCRIMP FRP Deck

Level 1/Level 2 Cost Categories	Per M^2	Per Ft^2	Total
Construction			
Agency Costs	$448.10	$45.65	$541,420
User Costs	$15.54	$1.44	$18,774
Total Construction	**$463.64**	**$43.19**	**$560,194**
Operation, Maintenance, & Repair			
Agency Costs	$23.75	$2.21	$28,691
User Costs	$29.50	$2.74	$35,643
Total Operation, Maintenance, & Repair	**$53.25**	**$4.95**	**$64,335**
Disposal			
Agency Costs	$6.01	$0.56	$7,262
User Costs	$2.28	$.021	$2,757
Total Disposal	**$8.29**	**$0.77**	**$10,019**
Grand Total Life-Cycle Cost	**$525.21**	**$48.81**	**$634,548**
Remark: Total Agency Costs	$477.89	$44.41	$577,374
Remark: Total User Costs	$47.32	$4.40	$57,174
Remark: Level-3 NTI Costs	$71.49	$6.64	$86,374

Note: All figures are listed in present-value dollars.

3.2.3 LCC of Wood-Core FRP Deck

The second FRP alternative is simple in design and light. At present it does not lend itself to design as part of a monolithic deck-beam assembly (see Figure 9) like the SCRIMP and concrete decks do. Figure 13 shows a schematic of the wood-core FRP material.

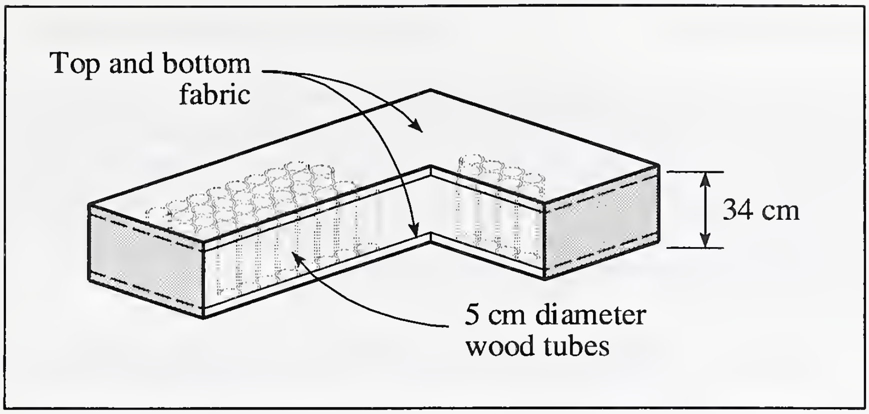

Figure 13. Wood-Core FRP Deck Material

Each decking section is 2.4 m (8 ft) wide by 18.3 m (60 ft) long and is composed of 1.9 cm (¾ in) top and bottom fiberglass layers, with a core composed of 5.1 cm (2 in) diameter by 30 cm (12 in) long vertical Asian structural bamboo sections bonded together with resin. Fiberglass fabric is soaked in vinyl ester and then applied to the top, bottom and sides. The left edge of each 2.4 m (8 ft) wide strip is stepped so that adjoining deck sections overlap; the sections are bonded at this overlap and the seam sanded before applying a 1.9 cm (¾ in) polymer-concrete wear surface. The resulting deck has twice the AASHTO factor of safety for deck strength.

Attachment to the beams is similar to that for the SCRIMP deck. Elastomer bearings are laid along the top of the beams. The decking is anchored to the beams, and then the metal barriers, center median, and polymer concrete are applied to the top surface of the deck. Beam strength is increased to account for the non-monolithic deck-beam design (see Figure 9).

3.2.3.1 Level 1 Initial Construction Costs

Agency elemental costs are estimated as follows: the manufacturer budgets fabrication at $129,000, and onsite installation at 400 labor-hours. The cost of shipping, elastomeric bearings, guardrail, center median and polymer-concrete asphalt are the same as for the SCRIMP deck. In addition, a surcharge is added for increasing the strength of the prestressed concrete beams to account for the non-monolithic deck-beam design. Agency activities to research and monitor the new material are the same as for the SCRIMP deck. User costs are calculated using eqs (3.1), (3.2), and (3.3), and are based on 10 roadwork days.

3.2.3.2 Level 1 Operation, Maintenance, and Repair Costs

Because no noticeable difference was discerned between SCRIMP and wood-core inspection time and repair procedures, the wood-core deck's OM&R agency costs and user costs are the same as for the SCRIMP deck.

3.2.3.3 Level 1 Disposal Costs

The wood-core deck is cut into 2.4 m (8 ft) wide sections by sawing the seams over the beams. Each strip is then pulled off the bridge in the direction of on-bridge traffic, reducing under-bridge traffic delays. Total number of disposal days is estimated to be six (source: wood-core deck fabricator). Disposal agency costs are based on 200 labor-hours at $15/hr plus the same $9,500 dump fee estimated for disposal of the SCRIMP deck. Table 3 lists the total LCC as well as breakdowns by level 1 and level 2 categories. Appendix C lists all costs estimated for the wood-core deck.

Table 3. Life-Cycle Cost of Wood-Core FRP Deck

Level 1/Level 2 Cost Categories	Per M^2	Per Ft^2	Total
Construction			
Agency Costs	$256.73	$23.86	$310,170
User Costs	$11.95	$1.11	$14,441
Total Construction	**$268.68**	**$24.97**	**$324,611**
Operation, Maintenance, & Repair			
Agency Costs	$23.75	$2.21	$28,691
User Costs	$29.50	$2.74	$35,643
Total Operation, Maintenance, & Repair	**$53.25**	**$4.95**	**$64,335**
Disposal			
Agency Costs	$3.27	$0.30	$3,947
User Costs	$6.85	$0.64	$8,270
Total Disposal	**$10.11**	**$0.94**	**$12,217**
Grand Total Life-Cycle Cost	**$332.04**	**$30.86**	**$401,163**
Remark: Total Agency Costs	$283.74	$26.37	$342,808
Remark: Total User Costs	$48.29	$4.49	$58,355
Remark: Level 3 NTI Costs	$71.49	$6.64	$86,374

Note: All figures are listed in present-value dollars.

3.2.4 LCC of Pultruded-Plank FRP Deck

Our final alternative deck is a proprietary product fabricated by the common FRP pultrusion process. Fiberglass wetted with vinyl ester is pulled through a heated die shaped like the cross-section shown in Figure 14. Long key strips allow three, 20.3 cm (8 in), pultruded planks to be joined, making a single .61 m (2 ft) wide plank. Because the planking runs transverse to traffic flow and has gaps every .61 m (2 ft), the decking cannot act as a compression flange, preventing a monolithic deck-beam design. As with the wood-core deck, the beams specified in the NCDOT drawings must be strengthened to account for the deck not contributing to the resistance of flexural bending in the beams. A three-rail metal guard barrier is installed along both sides of the deck. A concrete center median is installed, and polymer-concrete asphalt laid as the final road surface.

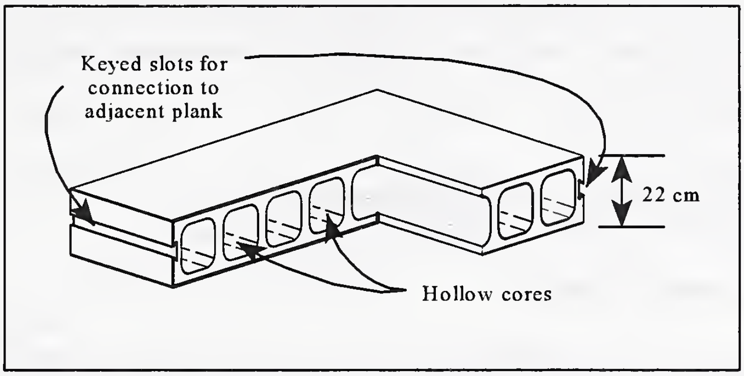

Figure 14. Pultruded-Plank FRP Deck

3.2.4.1 Level 1 Initial Construction Costs

Most of the agency costs, including NTI costs, are the same as for the wood-core deck but with the following exceptions. The material cost estimate is \$247.80/m^2 (\$23/ft^2), and labor costs are \$53.8/m^2 (\$5/ft^2).[48] Although the particular brand of pultruded FRP has been used in England, it is assumed that a U.S. state DOT would go through all of the new-material steps listed in section 3.2.2.1. User costs are calculated the same way as they are for the previous material/designs, but with an estimated 21 days of roadwork delays.

3.2.4.2 Level 1 Operation, Maintenance, and Repair Costs

Agency costs for deck maintenance and repair are based on the typical biannual inspection, a supplementary inspection in Year 25, and repair of the deck which involves replacement rather than repair of plank sections. The costs of both types of inspection are the same: \$100 and \$500 per inspection, respectively. An estimated 10.2 m^2 (110 ft^2) is replaced every three years from Year 25 to Year 37 at a

[48] All cost figures, material specifications, and methods for installing, repairing and disposing of the pultruded-plank FRP deck are based on discussions with Brian Wilson, Wilson Composites Group, Inc.

labor and material cost of $34/m^2 ($32/ft^2) (including polymer concrete on the new sections). Polymer concrete on existing sections is replaced at the same rate as for the other two alternatives: 650 ft^2 in Year 25 at a cost of $2/ft^2. Agency NTI costs are the same as for the other two alternatives, but exclude the cost to develop a non-destructive evaluation plan; this could be provided by the manufacturer. The number of days during which traffic is interrupted is 1 for standard inspection, 1 for supplemental inspection, 2 for deck replacement, and 3 for polymer-concrete patching.

3.2.4.3 Level 1 Disposal Costs

Agency costs of disposal are for removal of the entire deck. The estimated cost for disposal is based on 200 labor-hours and the same dumping fee as the other two FRP decks. Five calendar days is required for disposal; all other parameters for computing user costs of disposal are the same.

Table 4 lists total life-cycle, total agency, and total user costs for the pultruded plank deck, as well as breakdowns by level 1 and level 2 categories. Appendix C lists all of the life-cycle costs described in sections 3.2.4.1 through 3.2.4.3.

3.3 LCC and Net Savings Comparison of Decks

3.3.1 LCC Comparison of Decks

Figure 15 summarizes the life-cycle cost of the base-case concrete deck and the three FRP decks. For each of the four materials, the LCC is broken down according to the three classification levels. Note that the LCC is the same for a given material no matter which "level" of cost classification is used.

Looking at the level 1 cost breakdown, the concrete deck has the lowest construction cost ($225,327), but relatively high OM&R and disposal costs ($44,691 and $75,356, respectively). The wood-core deck, on the other hand, has higher construction and OM&R costs ($324,611 and $64,335, respectively) but is significantly less expensive to dispose of ($12,217). Turning to the level 2 cost breakdown, the wood-core deck has higher agency costs than the concrete deck ($342,808), but lower costs for direct users of the highway ($58,355). Finally, at the level 3 cost breakdown, all three alternatives have the same NTI costs ($86,374), but these costs are varying percentages of the total LCC.

If NTI costs are not included as part of normal bridge funding (e.g., come out of R&D funds), then the total LCC costs for all four alternatives are the remaining level 3 elemental cost values, as shown in the right-hand column in Table 5.

Table 4. Life-Cycle Cost of Pultruded-Plank FRP Deck

Level 1/Level 2 Cost Categories	Per M^2	Per Ft^2	Total
Construction			
Agency Costs	\$446.27	\$41.47	\$539,170
User Costs	\$25.10	\$2.33	\$30,327
Total Construction	**\$471.36**	**\$17.33**	**\$569,497**
Operation, Maintenance, & Repair			
Agency Costs	\$44.17	\$2.21	\$53,361
User Costs	\$32.69	\$2.74	\$39,497
Total Operation, Maintenance, & Repair	**\$76.85**	**\$7.14**	**\$92,859**
Disposal			
Agency Costs	\$3.27	\$0.30	\$3,947
User Costs	\$5.71	\$0.53	\$6,892
Total Disposal	**\$8.97**	**\$0.83**	**\$10,839**
Grand Total Life-Cycle Cost	**\$557.20**	**\$51.78**	**\$673,195**
Remark: Total Agency Costs	\$493.70	\$45.88	\$596,478
Remark: Total User Costs	\$63.50	\$5.90	\$76,716
Remark: Level-3 NTI Costs	\$71.49	\$6.64	\$86,374

Note: All figures are listed in present-value dollars.

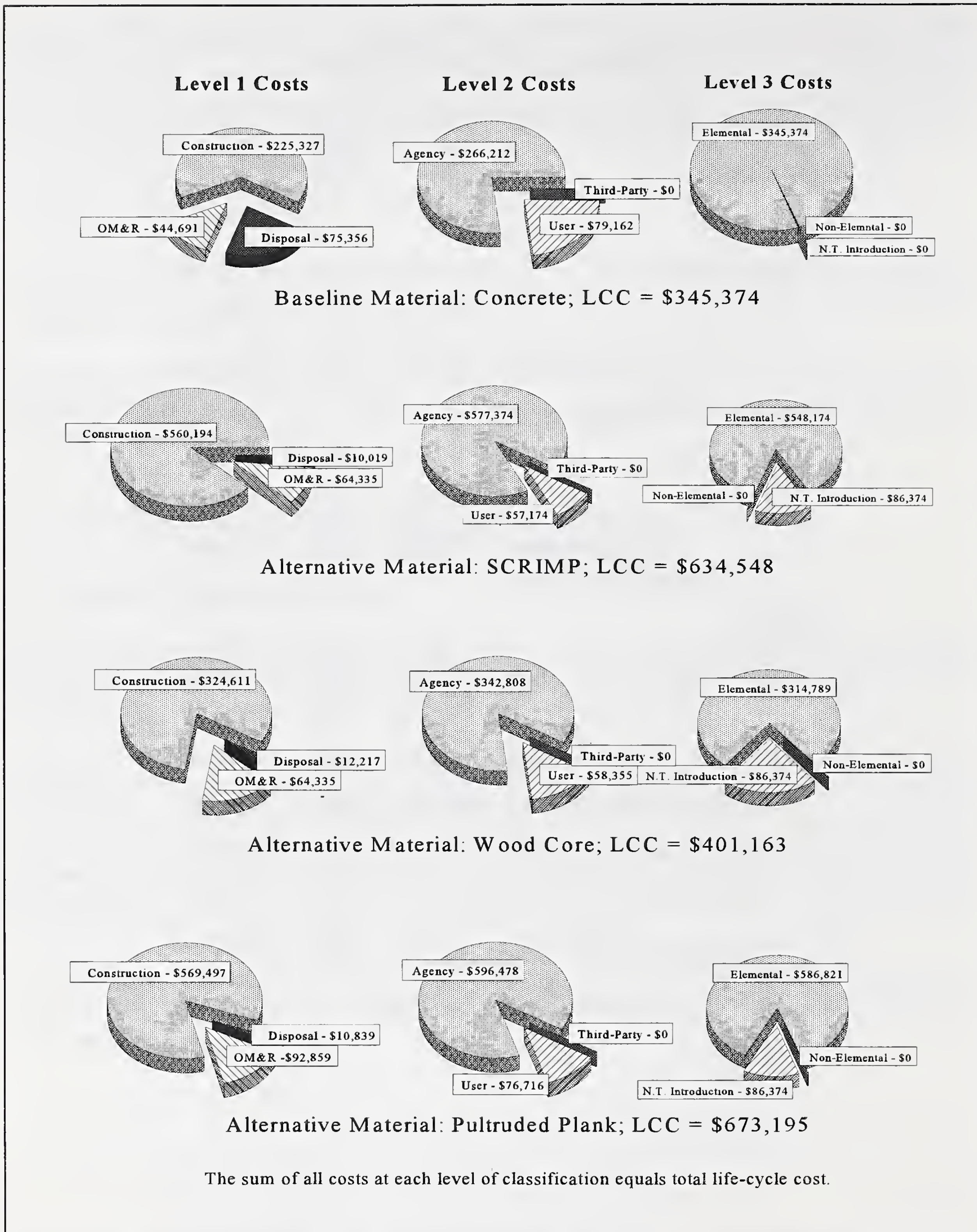

Figure 15. LCCs, with New-Technology Introduction Costs

Table 5. LCC of Material Alternatives, with and without NTI Costs

Material	LCC with NTI Costs	LCC without NTI Costs
Reinforced Concrete	**$345,374**	$345,374
SCRIMP FRP	$634,548	$548,174
Wood-Core FRP	$401,163	**$314,789**
Pultruded-Plank FRP	$673,195	$586,821

Note: The figures in bold indicate the cost-effective bridge deck material.

In the case without NTI costs the wood-core deck is the most cost-effective deck alternative rather than the base-case concrete deck. Comparing LCCs without the NTI costs is appropriate, for over the long run, these costs will both dissipate with increased applications and be shared over a larger number of applications.

3.3.2 Net Savings Comparison of Decks

Another way of determining the cost-effective alternative is to compute the net savings of each alternative in relation to the base case. We use eq (3.4) for computing the net savings of an alternative material design.

$$Net\ Savings_i = LCC_{Baseline} - LCC_{Alt.i}, \tag{3.4}$$

where

$LCC_{Alt.i}$ = life-cycle cost of the alternative *i* deck, and
$LCC_{Base\ case}$ = life-cycle cost of the base-case deck.

Tables 6 and 7 display the net savings for each alternative with breakdowns by level 1 and level 2 categories. Table 6 includes the NTI costs. Table 7 does not include them.

When NTI costs are included in total LCC (Table 6), all three alternatives have positive net savings for agency and user disposal costs, as well as for user construction costs. But all other categories of cost have negative net savings values.

When NTI costs are ignored (Table 7), all level 1 and level 2 categories of cost have positive net savings vis-a-vis the concrete deck except for agency costs during construction and the pultruded-plank deck's

Table 6. Net Savings of Alternative Decks, with NTI Costs

	SCRIMP	Wood Core	Pultruded
Initial Construction			
Agency	($346,420)	($115,170)	($344,170)
User	$11,553	$15,886	$245
Total	**($334,867)**	**($99,284)**	**($344,170)**
OM&R			
Agency	($19,051)	($19,051)	($43,722)
User	($592)	($592)	($4,446)
Total	**($19,644)**	**($19,644)**	**($48,168)**
Disposal			
Agency	$54,310	$57,625	$57,625
User	$11,027	$5,514	$6,892
Total	**$65,337**	**$63,139**	**$64,517**
Grand Total	**($289,174)**	**($55,789)**	**($327,821)**

Table 7. Net Savings of Alternative Decks, without NTI Costs

	SCRIMP	Wood Core	Pultruded
Initial Construction			
Agency	($285,920)	($54,670)	($344,170)
User	$11,553	$15,886	$0
Total	**($274,367)**	**($38,784)**	**($344,170)**
OM&R			
Agency	$875	$875	($43,722)
User	$5,356	$5,356	($4,446)
Total	**$6,231**	**$6,231**	**($48,168)**
Disposal			
Agency	$54,310	$57,625	$57,625
User	$11,027	$5,514	$6,892
Total	**$65,337**	**$63,139**	**$64,517**
Grand Total	**($202,799)**	**$30,585**	**($327,821)**

agency and user costs during OM&R. Moreover, the wood-core deck has a total net savings of $30,585 over the concrete deck.

The LCC/net savings implications of this case study are that, while NTI costs may initially make new materials cost ineffective as compared to conventional materials, over time new-technology materials show promise in becoming cost effective. Furthermore, the LCC classification and model prescribed here help the analyst evaluate the likely economic impacts of these new-technology materials.

3.4 Breakeven and Sensitivity Analysis

Many of the underlying parameters for a new-technology material's agency and user costs are not known with great precision. Tools are available to deal with this uncertainty. The two we use here are breakeven analysis and sensitivity analysis.

3.4.1 Breakeven Analysis

Breakeven analysis indicates the maximum or minimum values of key parameters necessary for an alternative material/design to be cost effective. Table 8 lists the breakeven values for a subset of case study parameters, both with and without the new-technology introduction costs. The variables used here are only representative; the individual doing the LCC study must choose those variables considered most important to the analysis and economically feasible for testing.

The "Predicted Value" column lists the parameter values used in the LCC case study. The other three columns list the parameter values necessary to make the particular alternative cost effective, all other parameters held constant. For example, when including the new-technology introduction costs (Table 8), any one of the following changes to our case study's predicted values would result in the wood-core alternative becoming cost effective relative to concrete, other parameters remaining unchanged:

1. An increase in US17 ADT from 10,000 vehicles to 36,000 vehicles.
2. An increase in the number of projects sharing the new-technology material costs to 3.
3. Inclusion of level 3, third party lost-business costs at $4,000 per road work day.
4. A 43% decrease in the material cost of the wood-core FRP deck.

For the pultruded plank deck, there is no number of projects at which point the pultruded-plank FRP deck is cost effective; the same holds for third party lost-business costs and for material costs.

When NTI costs are not included in the total LCC (Table 9), the wood-core FRP deck is cost effective even before changes to parameter values, but there is still no lost-business cost sufficient to make the pultruded-plank deck preferable to the concrete deck.

Table 8. Breakeven Analysis, with NTI Costs

	Predicted Value	SCRIMP	Wood-Core	Pultruded-Plank
US17 ADT	10000	142000	36000	1300000
# projects sharing NTI costs	1	*	3	*
Lost business per work day	$0	$25,000	$4,000	*
% decrease in material price	0%	74%	43%	*
Cost per accident	$103,000	$4,429,000	$999,100	$45,320,000
Kph on US17 during roadwork	88 kph	11	38	2

Note: A single asterisk indicates that there was no parameter value at which the alternative was cost effective vis-a-vis the base-case deck material.

Table 9. Breakeven Analysis, without NTI Costs

	Predicted Value	SCRIMP	Wood-Core	Pultruded-Plank
US17 ADT	10000	85000	**	300000
Lost business per work day	$0	$17,000	**	*
% decrease in material price	0%	52%	**	81%
Cost per accident	$103,000	$2,472,000	**	$9,785,000
Kph on US17 during roadwork	88 kph	24	**	6

Note: A single asterisk indicates that there was no parameter value for which the alternative was cost effective vis-a-vis the base-case deck material. A double asterisk indicates that the alternative is cost effective at the current parameter value.

3.6.2 Sensitivity Analysis

Sensitivity analysis measures the effect of key parameter changes on total LCC. Figure 16 shows for the concrete and SCRIMP decks the percent change in total LCC given a 10% change in a representative group of parameters. The parameters are listed from top to bottom in increasing level of significance in their effects on LCC.

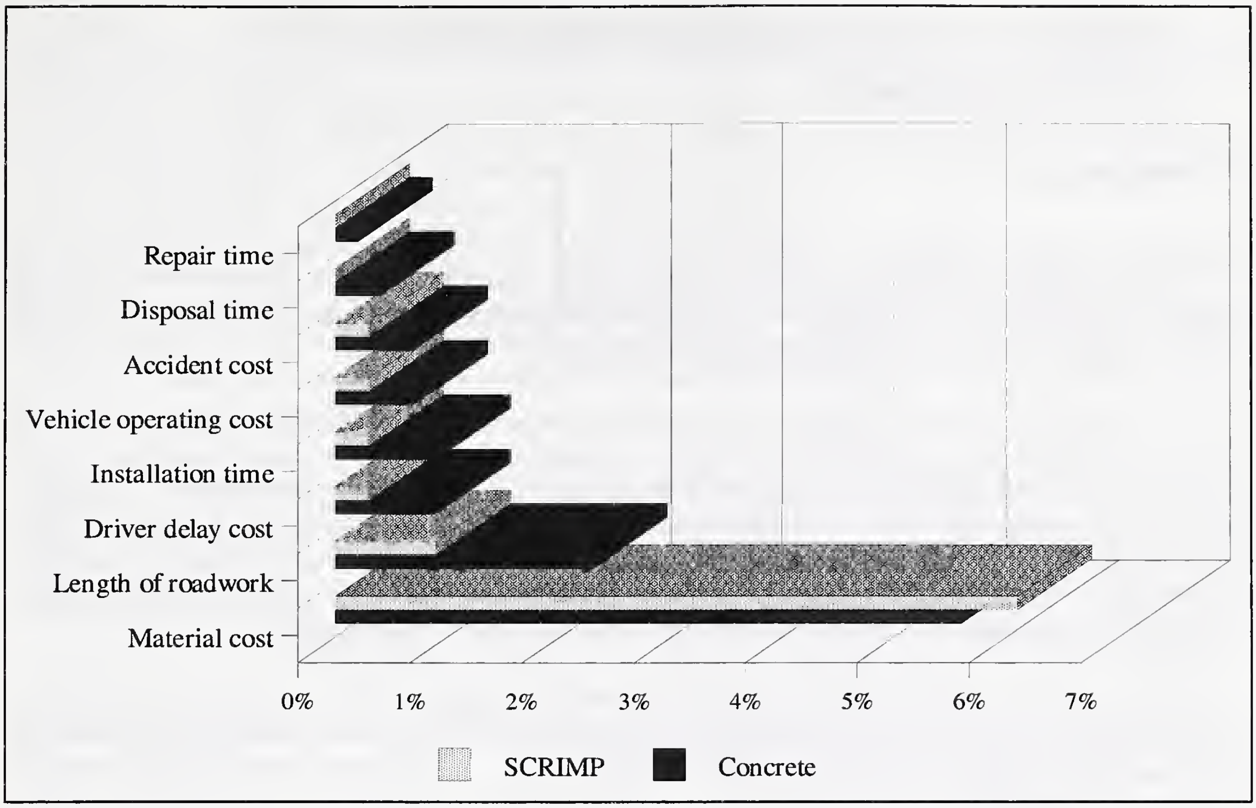

Figure 16. LCC Sensitivity of Concrete and SCRIMP Decks to Selected Parameters

Among the representative group of parameters, total LCC is most sensitive to variability in material cost and the length of roadwork. A 10% increase in SCRIMP material costs causes almost a 6% increase in LCC, all other parameters remaining unchanged. On the other hand, LCC is relatively insensitive to changes in the time required to perform repairs or to dispose of the structure. This is due in part to the discounting of the future repair and disposal costs to present values.

4. Summary, Conclusions, and Suggestions for Further Research

4.1 Summary

This report develops a model for evaluating the life-cycle cost (LCC) effectiveness of both conventional and new-technology materials in construction applications. The model consists of an LCC method for computing the relative LCCs of alternative materials and a hierarchical classification of project costs to help users of the method identify all costs appropriate for analysis.

The LCC method helps decision makers with three types of economic decisions for mutually exclusive alternatives: whether it is cost effective to accept or reject a project; what material/design is most cost effective; and what is the economically efficient level or size of a project. This report focuses on using the LCC method to choose the most cost-effective material/design alternative when new-technology materials are among the options. We use the term "material/design" alternative because new-technology materials typically call for new designs unique to them. The model is most helpful at the preliminary design stage, when large savings can be achieved from choosing a cost-effective material/design.

The LCC method is consistent with the standard method of performing life-cycle costing (E-917) published by the American Society for Testing and Materials. The method also complies with federal mandates such as the Intermodal Surface Transport Efficiency Act and Executive Order 12893 on Principles of Federal Infrastructure Investment.

To implement the model, the life-cycle costs (i.e., initial construction; operation, maintenance, and repair; and disposal costs) of each material/design alternative are computed in present value terms for the chosen study period of the analysis. Each alternative, to be technically viable as a candidate material, must at least meet the minimum performance specifications for that material in the project application. Typically the alternative with the lowest initial construction cost, which is often the conventional material, will be the base-case alternative. The most cost-effective material/design alternative is the one with the lowest LCC, or, said another way, with the greatest net savings when its LCC is compared against the LCC of the base case.

Measuring the LCC of new-technology materials requires that you identify new-technology introduction (NTI) costs. Examples of NTI costs are the extra time and labor to design, test, and monitor the new technology. Our model contains a taxonomy or classification of LCCs (Figure 3) to help users of the methodology identify and include all relevant costs, including NTI costs, in the LCC comparison. The classification is a three-level hierarchy. The first level groups costs by one of three categories: construction; operation, maintenance, and repair; and disposal. This is the grouping usually seen in a LCC formulation. The second level groups costs by the entity that incurs them—a government agency or company that builds the project; users of the project; and third parties that are affected indirectly by the project but who do not participate in building or using it. An example of a user cost is the time lost in traffic waiting to get around the construction site. An example of a third-party cost is the loss in revenue to a business adjacent to the construction site when access is cut off for customers. The third level of the LCC classification groups costs by elements or components of the project's structure, sometimes referred to as component systems or assemblies. This is the category in which we include the NTI costs.

We illustrate the model with a case study that compares the LCC of three, fiber-reinforced-polymer (FRP) bridge decks against the LCC of a conventional concrete bridge deck. Each deck alternative satisfies AASHTO load requirements and is under consideration by at least one state department of transportation. Our case-study prototypical bridge is currently under construction in Brunswick County, North Carolina. It is a two-lane overpass that covers a four-lane interstate. Each of the four material/design alternatives meet the requirements and specifications of the North Carolina bridge.

The base-case deck is a reinforced concrete slab. The three FRP composite decks are (1) SCRIMP—a form of vacuum-assisted resin transfer molding; (2) Wood-Core Sandwich—vertical Asian structural bamboo assembled into a rigid core with fiberglass and resin applied on all sides; and (3) Pultruded Plank—lineal planks pultruded from resin-wetted fiberglass fabric and fiberglass strand, with key strips to join them in a wider cross-section.

In the LCC comparison of the four decks, all costs identified in the LCC classification were estimated. While agency costs and user costs were identified for each alternative, no third-party costs were found due to the rural location of the bridge. When NTI costs were included in LCC, the reinforced concrete deck was the most cost-effective alternative. For example, its LCC was estimated at $345,000 compared to a LCC of $673,000 for the pultruded-plank FRP, which was the most expensive alternative. On the other hand, if NTI costs of the wood-core FRP deck were divided among three or more similar projects, it became the cost-effective choice. The significance of seeing a new-technology material become cost effective when NTI costs are spread out or removed is that, in the long run, NTI costs will dissipate with increased applications and be shared over an increasing number of projects. So while the new-technology material is not perhaps cost effective in its initial applications, the LCC model helps identify technologies that over time promise to be cost effective.

4.2 Conclusions

The LCC model presented in the report is useful in evaluating new-technology materials. Standard LCC methods are appropriate for determining the relative economic efficiency of new materials in relation to conventional materials. Having a standardized LCC tool available to evaluate new-technology materials/designs will encourage decision makers to consider alternatives on economic grounds that heretofore would have been considered too uncertain.

The LCC classification that itemizes NTI costs helps assure users of the LCC model that all relevant costs are accounted for in the analysis. This too will encourage planners at the predesign stage to estimate these NTI costs and use them in considering alternatives. And as the hard-to-estimate costs associated with the introduction of new technologies become more available, planners will likely pay more attention to those new technologies.

The major conclusion to be drawn from the case illustration of composite bridge decks is that, once a new technology such as an FRP composite begins to be applied and accepted, its LCC will diminish, making it more cost competitive with conventional materials. This happens for three reasons. First, spreading the NTI costs of a composite bridge over multiple bridges of similar design can reduce the LCC per bridge significantly, as shown by the relatively large slice of NTI costs in wood-core's LCC pie (Figure 15). Second, NTI costs diminish over time as the behavior and performance of the material/design become more certain and users accept it, thereby reducing the cost of material testing. Third, as economies of scale

in manufacturing occur with increasing applications and increased demand for the material, and the number of competing material's suppliers and fabricators increases, the cost of the new material itself will diminish.

Another conclusion from the case illustration is that new technologies can have certain cost advantages over conventional materials. For example, as shown by the pie charts in Figure 15, user costs associated with the bridge deck replacements are lower for the composite bridges due to reduced periods of traffic congestion.

While the case study focuses on composite bridge decks, the model it illustrates is applicable to any kind of new-technology (or conventional) material application to construction and building. The elemental cost classification focuses on bridge work in particular, but the NTI costs are generalizable to all kinds of infrastructure and building construction.

The model and case study might at first glance appear to be directed exclusively toward government agency use, since bridges are typically owned and maintained by government bodies, and public officials are expected to consider user costs and third-party effects. In addition, given the state of the nation's infrastructure, there is ample opportunity for applying the model in the public sector. The model is equally applicable, however, for private sector use. A private company building a new process plant or research laboratory, for example, has a multitude of new-technology material/design choices to which LCCs are sensitive. Given the public requirements that private companies be more sensitive to environmental and other external impacts from their activities, the model provides a guideline for companies to follow to ensure that all LCC impacts of its material choices are considered. But even if the company chooses to ignore some of the third-party or user costs associated with the alternatives, the model framework is appropriate for guiding material/design decisions.

4.3 Suggestions for Further Research

Our research and analysis for this report identified several additional research products that would be helpful for making choices between existing and new-technology building and construction materials. We describe the proposed projects in the order that they would be undertaken.

4.3.1 Risk and Uncertainty Analysis of Economic Estimates

Investments in long-lived projects such as bridges and buildings are characterized by uncertainties regarding project life, operation and maintenance costs, replacement intervals and costs, revenues, and other factors that affect project economics. Since future values of these variables are not known, it is difficult to make reliable economic evaluations.

Traditional economic analyses typically use "best estimates" of project input variables as if they were certain estimates and then present economic measures of worth in single-value, deterministic terms. Evaluating investment projects without regard to uncertainty of inputs to the analysis leaves decision makers insufficient information to measure and evaluate the risk of investing in a project having a different outcome than what is expected.

This research project would provide a simulation technique for treating uncertainty and risk in project evaluation.[49] Simulation provides a measure of risk exposure by allowing the analyst to build a cumulative distribution function that describes the probabilities of a measure of project worth being less than a target or minimum required value for economic efficiency.

The risk analysis technique will be packaged with the user-friendly decision-support software described in section 4.3.2 to give the user the computer capability of implementing the risk analysis technique.

4.3.2 User-Friendly Decision Support Software

Users of economic evaluation methods are sometimes discouraged from performing economic analysis by the technical knowledge (economic, statistical, mathematical, computer) requirements; the burden of collecting, manipulating, and calculating measures of worth from the input data; and the mysteries of how to interpret calculated measures of economic worth. Provision of user-friendly decision-support software overcomes some of these impediments to implementing economic methods in choosing among materials.

Whereas the methodology presented in this report is general enough to be used in any application that calls for life-cycle costing or net savings analysis, the software to be developed would be most useful if focused on a specific use. We recommend the development of software that targets bridge management officials to help them make economically sound decisions among competing bridge materials. The software will use the model as applied in the bridge deck case study in this report as the economic basis of the program.

The software will facilitate data entry by asking for all of the input values required in an economic analysis. Help screens will be available for critical inputs such as the discount rate and study period. The software will provide printed reports of costs, savings, and material descriptions. A classification of the types of costs unique to bridge construction and maintenance, as well as the costs unique to the introduction of new technology materials, will ensure that the user considers all possible costs and savings. Algorithms for calculating cost savings from reduced waiting times at construction sites and for calculating other unique costs associated with different material choices will be included in the software. The program will perform the calculations to arrive at life-cycle costs and net savings for the alternative materials, taking into account the time value of money.

A summary report showing the life-cycle costs of each material alternative and the net savings of each alternative relative to a base case material will give bridge project designers and managers the economic information they need to make material choices.

Finally, the software will encourage bridge managers to consider the economics of more materials because doing the analysis and reporting the findings will be much quicker than attempting it by hand. And the reporting of the relative economic merits of alternative materials will be in a format that helps the user interpret properly the relative economic impacts.

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[49]For a detailed description of simulation and other techniques for handling uncertainty and risk, see Harold E. Marshall, "Economic Methods and Risk Analysis Techniques for Evaluating Building Investments—A Survey," *CIB Report Publication 136*, February 1991.

4.3.3 Multiattribute Decision Analysis

Analysts typically perform economic analyses of capital investment alternatives using life-cycle cost comparisons, net savings, benefit-to-cost ratios, or other conventional measures of economic worth. A common characteristic of these economic worth measures is that they consider only *monetary* benefits or costs associated with investment alternatives. Yet building investment alternatives may differ in characteristics which decision makers consider important, but which are not readily expressed in monetary or even quantifiable terms.

Bridge materials, for example, may have characteristics or attributes other than those directly measurable in economics terms that influence their desirability. The appearance of the bridge material and design may be important for making an architectural statement. The noise generated by the bridge could be a consideration. And the bridge managers might want a bridge constructed from "green" materials so that they are environmentally friendly. While these attributes of appearance, noise, and environmental friendliness are important to bridge builders and users, there is no obvious way to combine them into a traditional, single, dollar measure of project economic worth.

This proposed research would develop a multiattribute decision analysis (MADA) technique[50] for making decisions where non-monetary or non-quantifiable considerations are important. The MADA technique allows users to account for project characteristics or attributes of a general nature (i.e., non-quantitative or non-monetary) when choosing among alternatives. Moreover, it allows the decision maker to incorporate the traditional economic measures of worth in the final comparison scores for each project alternative. That is, life-cycle costs (and therefore first costs) become one of the attributes in the MADA analysis. The analytical hierarchy method (AHP) is the MADA technique that will be proposed. It will be illustrated in several case studies of choosing materials for bridge construction and major material replacements. Ultimately the software described in section 4.3.2 for choosing bridge materials will be extended to incorporate the evaluation of non-monetary considerations with the net dollar savings measure of project effectiveness.

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[50] For a detailed description of MADA techniques, see Norris and Marshall, *Multiattribute Decision Analysis Method for Evaluating Buildings and Building Systems*, 1995.

Appendix A: Professional Profiles

MARK A. EHLEN

Dr. Ehlen is an industry economist with the Office of Applied Economics at the National Institute of Standards and Technology. In addition to developing methodologies for applying life-cycle cost and other economic techniques to the materials, design, and construction industries, he is conducting empirical studies of the macroeconomic impacts of NIST's Manufacturing Extension Partnership (MEP) and Advanced Technology Program (ATP). A graduate of Cornell University (Ph.D. in economics, 1996; M.A. in economics, 1994; and B.S. in civil/structural engineering, 1983), Dr. Ehlen previously worked as a civil engineer for a consulting firm in Santa Barbara, California, as a cost engineer and project scheduler for Dillingham Construction Company in Honolulu, Hawaii, and as a project manager for a general contractor in Rockville, Maryland.

HAROLD E. MARSHALL

Dr. Marshall heads the Office of Applied Economics at the National Institute of Standards and Technology. His specialty is developing standard economic methods and risk analysis techniques for evaluating investment projects. Dr. Marshall is co-author of the book *Building Economics: Theory and Practice*, and has published over 40 articles, chapters in books, and technical reports. He chairs, for the American Society for Testing and Materials, The Building Economics Subcommittee which has produced 11 standard economic methods used worldwide for evaluating investments in buildings and construction. He wrote and produced two widely circulated video training films—"Choosing Economic Evaluation Methods," and "Uncertainty and Risk." He was also featured as a subject matter expert in those videos and in a third video, "Introduction to Life-Cycle Costing." His post as advisory editor to the international journal *Construction Management and Economics* helps keep him abreast of developments abroad in building economics. A graduate of The George Washington University (Ph.D. in 1969, M.A., 1965, and B.A., 1964), Dr. Marshall's early career included teaching economics for two years on World Campus Afloat's around-the-world shipboard college, and performing economic research at the Department of Agriculture. In recognition of his contributions in building economics, Dr. Marshall received in 1978 the Department of Commerce's Silver Medal Award, in 1986 the American Association of Cost Engineers' highest honor, the Award of Merit, and in 1988 the American Society for Testing and Materials' Award of Merit and accompanying honorary title of Fellow of the Society.

Appendix B. Glossary of Key Terms

Accept/Reject Decision—A decision of whether or not to undertake a project.

Agency Costs—All costs incurred by the project's owner or agent over the study period. These include design costs, capital costs, insurance, utilities, servicing and repair, and disposal of the facility.

Base-Case Alternative—The alternative whose LCC is compared against the LCC of alternative materials or designs. The base case is typically the one with the lowest initial cost.

Base Year—The common year to which all project costs are converted so that the LCCs of project alternatives can be compared. The base year is typically the first year of the study period, that is, the first year of the project life-cycle.

Breakeven Analysis—A technique for determining the maximum or minimum value that an uncertain variable must equal so that a project's benefits equal costs (i.e., breaks even).

Composite—A material fabricated from two or more materials. The composite material typically has one or more characteristics (such as strength, stiffness, and durability) that are different than those of its constituent materials.

Constant Dollars—Dollars of uniform purchasing power tied to a reference year (usually the base year) and exclusive of general price inflation or deflation.

Cost Effective—The condition whereby the present value net savings of an investment relative to the base case is positive, or, said another way, its LCC is lower than the LCC of the base case.

Current Dollars—Dollars of nonuniform purchasing power, including general price inflation or deflation, in which actual prices are stated. (With zero inflation or deflation, current dollars are identical to constant dollars.)

Deterministic Analysis—The approach to project evaluation in which "best-guess" estimates of project input values are used to compute a single-value measure of project worth.

Discount Rate—The minimum acceptable rate of return used in converting benefits and costs occurring at different times to their equivalent values at a common point in time. Discount rates reflect the investor's time value of money (or opportunity cost). Real discount rates reflect time value apart from changes in the purchasing power of the dollar (i.e., inflation or deflation) and are used to discount constant dollar cash flows. Market or nominal discount rates include changes in the purchasing power of the dollar and are used to discount current dollar cash flows.

Discounting—A procedure for converting a cash flow that occurs over time to an equivalent value at a common point in time.

Appendix B. Glossary of Key Terms (continued)

Disposal Costs—All expenses associated with removal or termination of the project, net of any salvage value the facility has at the end of the project.

Economically Efficient—The condition when an investment alternative has the minimum life-cycle cost among alternatives that meet performance requirements, or has the maximum net savings when compared to the base-case alternative.

Efficiency Level (Size) Decision—A decision of what level or size of investment to make while satisfying the project objective.

Elemental Costs—Costs directly attributable to major elements of the project. For example, major elements common to bridges are the deck, substructure, superstructure, and approaches.

Fiber-Reinforced Polymer (FRP)—A composite material formed by immersing continuous-strand e-glass or carbon fiber in resin.

Future Costs—Costs that accrue at some future time.

High-Performance Material—A construction material with characteristics—including strength and durability—which are significantly superior to traditional construction materials.

Infrastructure—The building structures, roadways, water systems, electrical networks, and communications systems that support a city, state, or nation.

Initial Construction Costs—Construction costs incurred at the beginning of the study period to cover all activities necessary to put the project into operation. These activities include final parametric design, permits, surveying, furnishing and installing all physical components of the structure, contingencies for expected change orders, and final inspection.

Jersey Barriers—Steel-reinforced concrete traffic guardrails for bridges and highways. They are placed on the right-hand side of a traffic lane or bridge and between lanes of opposing-direction traffic. They can be either installed as an integral, structural part of a roadway, or individual sections can be linked together longitudinally and simply placed on top of the road surface.

Life-Cycle Cost (LCC)—The sum of all discounted costs of acquiring, owning, operating and maintaining, and disposing of a structure or building over the study period. Comparing life-cycle costs among mutually exclusive projects of equal performance is one way of determining relative cost effectiveness.

Market Discount Rate (Nominal Discount Rate)—The rate of interest reflecting the time value of money stemming from both inflation and the real earning power of money over time.

Appendix B. Glossary of Key Terms (continued)

Material/Design Decision—A decision of which material/design among competing material/design alternatives to choose to satisfy the project objective.

Multiattribute Decision Analysis (MADA)—A family of methods of project evaluation that consider non-financial attributes (qualitative and quantitative) in addition to common financial worth measures.

Net Savings—The difference between the LCC of a base-case alternative and the LCC of an alternative, where both alternatives meet project performance requirements. The net savings (benefits) method is used to measure relative project worth.

New-Technology Introduction Costs (NTI)—Costs generated from activities which satisfy engineers, designers, and code officials that the new-technology material will perform as predicted. These activities include laboratory load testing of model structures, the use of outside design consultants, and non-destructive evaluation (NDE) of the new-technology materials over time.

New-Technology Material—A material with a new fabrication process, design method, or construction application such that its attributes (such as strength, lightness, ease of use, or cost) make it desirable compared to conventional construction materials.

Non-Elemental Costs—Project costs not directly assignable to a specific subcomponent of a project.

Operation, Maintenance, and Repair Costs—Costs necessary to operate the facility (such as utilities, security, and insurance) and to keep the facility up to performance requirements (such as periodic inspection, repairs, and replacement of structural elements).

Performance Requirements—The requirements that each project alternative must meet to be accepted as a viable means of satisfying the project objective. Examples are structural, safety, reliability, environmental, and specific building code requirements.

Polymer-Matrix Composite—See **Fiber-Reinforced Polymer**

Preliminary Design Phase—The sub-phase of the overall facility design process in which alternative construction materials and designs are evaluated, and the final choice of materials and designs is made.

Pultruded Plank—One of the case study, fiber-reinforced-polymer (FRP) bridge decks. Individual bridge deck sections are fabricated using the FRP pultrusion process.

Real Discount Rate—See **Discount Rate**

Appendix B. Glossary of Key Terms (continued)

Present Value—The time-equivalent value at a specified base time (in this case the present) of past, present, and future cash flows.

Products-Based Estimate—Project cost estimates based on the constituent materials and other resources used to construct, maintain and dispose of the project facility. The process of doing material take-offs from blueprints and assigning unit material, labor, and equipment costs to these materials is one form of a projects-based cost estimate.

Real Earning Opportunity of Money—The earning potential of money apart from the returns that reflect changes in the purchasing power of money (i.e., inflation or deflation).

SCRIMP (Seaman Composite Resin Infusion Molding Process)—A fiber-reinforced-polymer (FRP) fabrication process in which resin is pulled by vacuum through e-glass or carbon fiber fabric. The SCRIMP process was used in one of the case study FRP bridge decks.

Spillover Costs—The costs from a construction project that are borne by entities that are not directly involved in the project.

Study Period—The length of time over which an investment is evaluated.

Third Party Costs—See **Spillover Costs**

User Costs—The costs due to project activities that are borne by direct users of the project.

Wood-Core Sandwich—One of the case study, fiber-reinforced-polymer (FRP) bridge decks. The deck is composed of vertical, 2-inch diameter Asian structural bamboo sections which are compacted and then covered with e-glass fabric; resin is then applied to the fabric.

Appendix C: Case Study Cost Tabulation

Table C.1 Costs of Conventional Concrete Deck by Level

	Qtty	Umeas	U.C.	Start	End	Freq
L1: Initial Construction						
L2: Agency Costs						
L3: Elemental Costs						
Element 1						
Construct new deck	13000	sf	$15	1	1	1
L3: Non-Elemental Costs						
L3: New-Technology Introduction Costs						
L2: User Costs						
L3: Elemental Costs						
Element 1						
Construction: driver delay, vehicle and accidents	21	days		1	1	1
L3: Non-Elemental Costs						
L3: New-Technology Introduction Costs						
L3: 3rd Party Costs						
L3: Elemental Costs						
L3: Non-Elemental Costs						
L3: New-Technology Introduction Costs						
L1: OM&R						
L2: Agency Costs						
L3: Elemental Costs						
Element 1						
Deck inspection	1	ls	$100	2	38	2
Supplementary deck inspection	1	ls	$500	25	25	1
Resurface 5% of deck	650	sf	$10	25	25	1
Resurface 2.5% of deck	325	sf	$10	28	37	3
L3: New-Technology Introduction Costs						

Legend: Qtty = quantity; Umeas = unit of measure; U.C. = unit cost; Start = first year in which cost occurs; End = last year in which cost occurs; Freq. = annual frequency with which cost occurs; sf = square feet; ls = lump sum; lhrs = labor hours; 1f = lineal feet.

Table C.1 Costs of Conventional Concrete Deck by Level

	Qtty	Umeas	U.C.	Start	End	Freq
L2: User Costs						
L3: Elemental Costs						
Element 1						
Inspection: driver delay, vehicle and accidents	1	ls		2	38	2
Suppl. inspection: driver delay, vehicle and accidents	1	ls		25	25	1
Resurfacing: driver delay, vehicle and accidents	1	ls		25	25	1
Resurfacing: driver delay, vehicle and accidents	1	ls		28	37	3
L3: Non-Elemental Costs						
L3: New-Technology Introduction Costs						
L3: 3rd Party Costs						
L3: Elemental Costs						
L3: Non-Elemental Costs						
L3: New-Technology Introduction Costs						
L1: Disposal						
L2: Agency Costs						
L3: Elemental Costs						
Element 1						
Disposal of deck	13000	sf	$15	40	40	1
L3: Non-Elemental Costs						
L3: New-Technology Introduction Costs						
L3: Elemental Costs						
Element 1						
Disposal: driver delay, vehicle and accidents	10	days		40	40	1
L3: Non-Elemental Costs						
L3: New-Technology Introduction Costs						
L2: User Costs						

Legend: Qtty = quantity; Umeas = unit of measure; U.C. = unit cost; Start = first year in which cost occurs; End = last year in which cost occurs; Freq. = annual frequency with which cost occurs; sf = square feet; ls = lump sum; lhrs = labor hours; 1f = lineal feet.

Table C.1 Costs of Conventional Concrete Deck by Level

	Qtty	Umeas	U.C.	Start	End	Freq
L3: 3rd Party Costs						
L3: Elemental Costs						
L3: Non-Elemental Costs						
L3: New-Technology Introduction Costs						

Legend: Qtty = quantity; Umeas = unit of measure; U.C. = unit cost; Start = first year in which cost occurs; End = last year in which cost occurs; Freq. = annual frequency with which cost occurs; sf = square feet; ls = lump sum; lhrs = labor hours; 1f = lineal feet.

Table C.2 Costs of SCRIMP FRP Deck by Level

	Qtty	Umeas	U.C.	Start	End	Freq
L1: Initial Construction						
L2: Agency Costs						
L3: Elemental Costs						
Element 1						
Factory fab	13000	sf	$30	1	1	1
Shipping	1	ls	$25,000	1	1	1
On-site fab: bearings	1	ls	$5,000	1	1	1
On-site fab: install	600	lhrs	$15	1	1	1
F&I metal guard rail	472	lf	$100	1	1	1
F&I median	236	lf	$20	1	1	1
Polymer concrete asphalt	13000	sf	$2	1	1	1
L3: Non-Elemental Costs						
L3: New-Technology Introduction Costs						
Pre-design NTM project formulation	50	lhrs	$50	1	1	1
Academic design consultant	1	ls	$20,000	1	1	1
Laboratory tests	1	ls	$30,000	1	1	1
Meetings with fabricator, review shop drawings	60	lhrs	$50	1	1	1
Field engineering, construction inspection	100	lhrs	$50	1	1	1
L2: User Costs						
L3: Elemental Costs						
Element 1						
Construction: driver delay, vehicle and accidents	13	days		1	1	1
L3: Non-Elemental Costs						
L3: New-Technology Introduction Costs						
L3: 3rd Party Costs						
L3: Elemental Costs						
L3: Non-Elemental Costs						
L3: New-Technology Introduction Costs						

Legend: Qtty = quantity; Umeas = unit of measure; U.C. = unit cost; Start = first year in which cost occurs; End = last year in which cost occurs; Freq. = annual frequency with which cost occurs; sf = square feet; ls = lump sum; lhrs = labor hours; 1f = lineal feet.

Table C.2 Costs of SCRIMP FRP Deck by Level

	Qtty	Umeas	U.C.	Start	End	Freq
L1: OM&R						
L2: Agency Costs						
L3: Elemental Costs						
Element 1						
Deck inspection	1	ls	$100	2	40	2
Supplementary deck inspection	1	ls	$500	25	25	1
Fiber patching	130	sf	$20	28	28	3
Polymer concrete patching	650	sf	$20	25	25	1
L3: Non-Elemental Costs						
L3: New-Technology Introduction Costs						
Develop non-destructive evaluation plan	100	lhrs	$50	1	1	1
Inspect deck: once month/1st year	28	lhrs	$30	1	1	0.0833
Inspect deck: once every 6 months/next 3 years	28	lhrs	$30	2	4	0.5
L2: User Costs						
L3: Elemental Costs						
Element 1						
Inspection: driver delay, vehicle and accidents	1	day		1	40	2
Suppl. inspection: driver delay, vehicle and accidents	1	day		25	25	1
Resurfacing: driver delay, vehicle and accidents	2	day		28	28	3
L3: Non-Elemental Costs						
L3: New-Technology Introduction Costs						
L3: 3rd Party Costs						
L3: Elemental Costs						
L3: Non-Elemental Costs						
L3: New-Technology Introduction Costs						

Legend: Qtty = quantity; Umeas = unit of measure; U.C. = unit cost; Start = first year in which cost occurs; End = last year in which cost occurs; Freq. = annual frequency with which cost occurs; sf = square feet; ls = lump sum; lhrs = labor hours; 1f = lineal feet.

Table C.2 Costs of SCRIMP FRP Deck by Level

	Qtty	Umeas	U.C.	Start	End	Freq
L1: Disposal						
L2: Agency Costs						
L3: Elemental Costs						
Element 1						
Disposal of deck L&E	300	1mhrs	$45	40	40	1
Dump fee	1	ls	$9,500	40	40	1
L3: Non-Elemental Costs						
L3: New-Technology Introduction Costs						
L2: User Costs						
L3: Elemental Costs						
Disposal: driver delay, vehicle and accidents	2	days		40	40	1
L3: Non-Elemental Costs						
L3: New-Technology Introduction Costs						
L3: 3rd Party Costs						
L3: Elemental Costs						
L3: Non-Elemental Costs						
L3: New-Technology Introduction Costs						

Legend: Qtty = quantity; Umeas = unit of measure; U.C. = unit cost; Start = first year in which cost occurs; End = last year in which cost occurs; Freq. = annual frequency with which cost occurs; sf = square feet; ls = lump sum; lhrs = labor hours; 1f = lineal feet.

Table C.3 Costs of Wood-Core FRP Deck by Level

	Qtty	Umeas	U.C.	Start	End	Freq
L1: Initial Construction						
L2: Agency Costs						
L3: Elemental Costs						
Element 1						
Factory fab	1	ls	$129,000	1	1	1
Shipping	1	ls	$25,000	1	1	1
5% beam surcharge	1	ls	$6,750	1	1	1
On-site fab: bearings	1	ls	$5,000	1	1	1
On-site fab: install	400	lhrs	$15	1	1	1
F&I metal guard rail	472	lf	$100	1	1	1
F&I median	236	lf	$20	1	1	1
Polymer concrete asphalt	13000	sf	$2	1	1	1
L3: Non-Elemental Costs						
L3: New-Technology Introduction Costs						
Pre-design NTM project formulation	50	lhrs	$50	1	1	1
Academic design consultant	1	ls	$20,000	1	1	1
Laboratory tests	1	ls	$30,000	1	1	1
Meetings with fabricator, review shop drawings	60	lhrs	$50	1	1	1
Field engineering, construction inspection	100	lhrs	$50	1	1	1
L2: User Costs						
L3: Elemental Costs						
Element 1						
Construction: driver delay, vehicle and accidents	10		days	1	1	1
L3: Non-Elemental Costs						
L3: New-Technology Introduction Costs						
L3: Elemental Costs						
L3: Non-Elemental Costs						
L3: New-Technology Introduction Costs						

Legend: Qtty = quantity; Umeas = unit of measure; U.C. = unit cost; Start = first year in which cost occurs; End = last year in which cost occurs; Freq. = annual frequency with which cost occurs; sf = square feet; ls = lump sum; lhrs = labor hours; 1f = lineal feet.

Table C.3 Costs of Wood-Core FRP Deck by Level

	Qtty	Umeas	U.C.	Start	End	Freq
L1: Maintenance & Repair						
L2: Agency Costs						
L3: Elemental Costs						
Element 1						
Deck inspection	1	ls	$100	2	40	2
Supplementary deck inspection	1	ls	$500	25	25	1
Fiber patching	130	sf	$20	28	28	3
Polymer concrete patching	650	sf	$20	25	25	1
L3: Non-Elemental Costs						
L3: New-Technology Introduction Costs						
Develop non-destructive evaluation plan	100	lhrs	$50	1	1	1
Inspect deck: once month/1st year	28	lhrs	$30	1	1	0.0833
Inspect deck: once every 6 months/next 3 years	28	lhrs	$30	2	4	0.5
L2: User Costs						
L3: Elemental Costs						
Element 1						
Inspection: driver delay, vehicle and accidents	1	day		1	40	2
Suppl. inspection: driver delay, vehicle and accidents	1	day		25	25	1
Resurfacing: driver delay, vehicle and accidents	2		days	28	28	3
L3: Non-Elemental Costs						
L3: New-Technology Introduction Costs						
L3: 3rd Party Costs						
L3: Elemental Costs						
L3: Non-Elemental Costs						
L3: New-Technology Introduction Costs						

Legend: Qtty = quantity; Umeas = unit of measure; U.C. = unit cost; Start = first year in which cost occurs; End = last year in which cost occurs; Freq. = annual frequency with which cost occurs; sf = square feet; ls = lump sum; lhrs = labor hours; 1f = lineal feet.

Table C.3 Costs of Wood-Core FRP Deck by Level

	Qtty	Umeas	U.C.	Start	End	Freq
L1: Disposal						
L2: Agency Costs						
L3: Elemental Costs						
Element 1						
Disposal of deck L&E	200	lhrs	$15	40	40	1
Dump fee	1	ls	$9,500	40	40	1
L3: Non-Elemental Costs						
L3: New-Technology Introduction Costs						
L2: User Costs						
L3: Elemental Costs						
Element 1						
Disposal: driver delay, vehicle and accidents	6	days		40	40	1
L3: Non-Elemental Costs						
L3: New-Technology Introduction Costs						
L3: 3rd Party Costs						
L3: Elemental Costs						
L3: Non-Elemental Costs						
L3: New-Technology Introduction Costs						

Legend: Qtty = quantity; Umeas = unit of measure; U.C. = unit cost; Start = first year in which cost occurs; End = last year in which cost occurs; Freq. = annual frequency with which cost occurs; sf = square feet; ls = lump sum; lhrs = labor hours; 1f = lineal feet.

Table C.4 Costs of Pultruded-Plank FRP Deck by Level

	Qtty	Umeas	U.C.	Start	End	Freq
L1: Initial Construction						
L2: Agency Costs						
L3: Elemental Costs						
Element 1						
Factory fab	13000	sf	$23	1	1	1
Shipping	1	ls	$25,000	1	1	1
5% beam surcharge	1	ls	$6,750	1	1	1
On-site fab: bearings	1	ls	$5,000	1	1	1
On-site fab: install	13000	sf	$5	1	1	1
F&I metal guard rail	472	lf	$100	1	1	1
F&I median	236	lf	$20	1	1	1
Polymer concrete asphalt	13000	sf	$2	1	1	1
L3: Non-Elemental Costs						
L3: New-Technology Introduction Costs						
Pre-design NTM project formulation	50	lhrs	$50	1	1	1
Academic design consultant	1	ls	$20,000	1	1	1
Laboratory tests	1	ls	$30,000	1	1	1
Meetings with fabricator, review shop drawings	60	lhrs	$50	1	1	1
Field engineering, construction inspection	100	lhrs	$50	1	1	1
L2: User Costs						
L3: Elemental Costs						
Element 1						
Construction: driver delay, vehicle and accidents	21	days		1	1	1
L3: Non-Elemental Costs						
L3: New-Technology Introduction Costs						
L3: 3rd Party Costs						
L3: Elemental Costs						
L3: New-Technology Introduction Costs						

Legend: Qtty = quantity; Umeas = unit of measure; U.C. = unit cost; Start = first year in which cost occurs; End = last year in which cost occurs; Freq. = annual frequency with which cost occurs; sf = square feet; ls = lump sum; lhrs = labor hours; 1f = lineal feet.

Table C.4 Costs of Pultruded-Plank FRP Deck by Level

	Qtty	Umeas	U.C.	Start	End	Freq
L1: Maintenance & Repair						
L2: Agency Costs						
L3: Elemental Costs						
Element 1						
Deck inspection	1	ls	$100	2	40	2
Supplementary deck inspection	1	ls	$500	25	25	1
Deck replacement	250	sf	$35	25	37	3
Polymer concrete patching	1430	sf	$20	25	25	1
L3: Non-Elemental Costs						
L3: New-Technology Introduction Costs						
Develop non-destructive evaluation plan	40	lhrs	$50	1	1	1
Inspect deck: once month/1st year	28	lhrs	$30	1	1	0.0833
Inspect deck: once every 6 months/next 3 years	28	lhrs	$30	2	4	0.5
L2: User Costs						
L3: Elemental Costs						
Element 1						
Inspection: driver delay, vehicle and accidents	1	day		1	40	2
Suppl. inspection: driver delay, vehicle and accidents	1	day		25	25	1
Resurfacing: driver delay, vehicle and accidents	3	day		28	28	3
L3: Non-Elemental Costs						
L3: New-Technology Introduction Costs						
L3: 3rd Party Costs						
L3: Elemental Costs						
L3: Non-Elemental Costs						
L3: New-Technology Introduction Costs						
L1: Disposal						
L2: Agency Costs						

Legend: Qtty = quantity; Umeas = unit of measure; U.C. = unit cost; Start = first year in which cost occurs; End = last year in which cost occurs; Freq. = annual frequency with which cost occurs; sf = square feet; ls = lump sum; lhrs = labor hours; 1f = lineal feet.

Table C.4 Costs of Pultruded-Plank FRP Deck by Level

	Qtty	Umeas	U.C.	Start	End	Freq
L3: Elemental Costs						
Element 1						
Disposal of deck - L	200	lhrs	$15	40	40	1
Dump fee	1	ls	$9,500	40	40	1
L3: Non-Elemental Costs						
L3: New-Technology Introduction Costs						
L2: User Costs						
L3: Elemental Costs						
Element 1						
Disposal: driver delay, vehicle and accidents	5	days		40	40	1
L3: Non-Elemental Costs						
L3: New-Technology Introduction Costs						
L3: 3rd Party Costs						
L3: Elemental Costs						
L3: Non-Elemental Costs						
L3: New-Technology Introduction Costs						

Legend: Qtty = quantity; Umeas = unit of measure; U.C. = unit cost; Start = first year in which cost occurs; End = last year in which cost occurs; Freq. = annual frequency with which cost occurs; sf = square feet; ls = lump sum; lhrs = labor hours; 1f = lineal feet.

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